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Socio Economic Research on Fusion

EFDA Technology Workprogramme 2011

WP11-SER-ETM-1.3.6

Activity 1.3.6. Modelling infrastructures

Association Euratom - DTU, Technical University of Denmark,
DTU, Risø Campus, Roskilde, Denmark

Final Report, April 2012

Poul Erik Grohnheit

Abbreviations

CCS	Carbon Capture and Storage
CHP	combined heat and power
CO_2	carbon dioxide
EFDA	European Fusion Development Agreement
EJ	Exajoule 10^{18} Joule
ETP	Energy Technology Perspectives (IEA)
ETSAP	Energy Technology Systems Analysis Programme
EU	European Union
GHG	Greenhouse gasses
Gt	Gigatonne
GW	Gigawatt
IEA	International Energy Agency
IGCC	Internal Gasification Combined Cycle power plant
IPCC	Ineregovernmental Panel on Climate Change
kt	Kilotonne
kW	Kilowatt
kWh	Kilowatt hour
LWR	Light water reactor
MARKAL	Market Allocation (optimisation model developed by the IEA)
Mt	Megatonne
MW	Megawatt
MWe	megawatt, electric
MWh	megawatt hours
NGCC	Natural Gas Combined Cycle power plant
PC	Pulverised coal-fired power plant
PET	Pan European TIMES (model)
PJ	Petajoule 10^{15} Joule
SERF	Socio Economic Research on Fusion
TIMES	The Integrated Markal EFOM System
TWh	terawatt hours 10^{12} Wh
VEDA	VErsatile Data Analyst
WEO	World Energy Outlook (IEA)

DISCLAIMER

This work, supported by the European Communities under the contract of Association between EURATOM/Risø DTU was carried out within the framework of EFDA. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Preface

This is the final report for Socio Economic Research on Fusion (SERF), EFDA Technology Workprogramme 2011, WP11-SER-ETM-1.3.6, Activity 1.3.6. Modelling infrastructures.

In addition the report describes the current status of the issues addressed in the previous workprogrammes.

- WP-2009, Activity 2.5: Update and validation of assumptions for technologies that will compete with fusion in the future, focussing on biomass and Carbon Capture & Sequestration (CCS)
- WP-2010, Activity 2: Fossil fuel dominance

DTU Risø Campus, (until December 2011 Risø DTU), Roskilde Denmark, April 2012

Poul Erik Grohnheit

1 Introduction

The impact of introducing infrastructure to EFDA-TIMES is very dependent on the contents and quality of the rest of the model. The impact may be nothing or quite significant. Therefore this report is based not only on the current task for WP11 but also activities under the previous Work Programmes.

The common methodology used for the description contains the following steps:

- Selection of 'Background scenario'
- Specification of new topology, processes and parameters
- Running multiple scenarios
- Presentation of results

1.1 Selection of background scenarios

In the final report from Risø DTU "Sensitivity Analyses of Biomass and CCS in EFDA-TIMES" (Activity 2.5 – July 2010) the aim was to identify the combination of assumptions that would allow biomass and CCS to play a significant role by 2050 and after. By the end of the century fusion might replace biomass or fossil fuel with CCS

This analysis requires that a stable scenario is available, which can be used as the background for numerous runs of the model – both parameter studies and modifications of the topology.

The background scenario is different from the Base Scenario, which has a minimum of constraints. The background scenario must have a set of constraints that will allow a broad range of scenarios to be chosen by the model. For the first analysis of CCS and biomass two constraints were chosen:

- Global electricity production in a carbon constrained scenario equivalent to restricting the atmospheric CO_2 concentration to 550 ppm (equivalent),
- Nuclear fission should not increase above 25 % of electricity generation each region during the rest of the century.

For the following analysis of fossil fuel dominance and infrastructure the more stringent CO_2 constraint at 450 ppm is preferred. This scenario had a feasible solution in the EFDA-TIMES version December 2009.

An Excel workbook was developed for the management of a large number of cases for sensitivity analysis, which is also used for other versions of TIMES, e.g. ETSAP-TIAM.

1.2 Issues addressed in recent workprogrammes

The framework for these issues was set up in Workprogramme 2009: Update and validation of assumptions for technologies that will compete with fusion in the future, focussing on biomass and Carbon Capture & Sequestration (CCS). The issues addressed in the following workprogrammes and their current status are summarised in Table 1.1. The focus has been to identify technologies, parameters and issues that are significant for technologies that will be competitive or complementary to fusion based power generation located in regions containing large population centres in the second part of the 21 Century.

Table 1.1. Issues addressed in workprogrammes 2010 and 2011.

WP 10: Addressing fossil fuels dominance issue	
Extension of the life of fossil fuels (especially coal) using the new Carbon Capture and Storage (CCS) technologies, even in stringent emission reduction scenarios.	CCS technologies hardly appear in EFDA_TIMES results.
Collection of available and future CCS technologies.	See Table 2.2. Efficiencies for new large gas and coal fired power plants and the same technologies with CCS.
Review of feasible storage options.	See Figure 3.1. Cumulative CO2 storage capacity,
Unconventional oil and gas resources: What are unconventional gas resources? How much gas is available in this form? Are mining technologies in sight and if yes.	Oil and gas will play a minor role for electricity generation in scenarios with CO_2 constraints, see Section 2.1.
WP 11: Modelling infrastructure	
Parameter studies: Variation of parameters for costs and efficiencies in the new aggregated technologies that was introduced in WP 2010: Large-scale cogeneration heat power (CHP) and heat transmission.	The original choice 25 $/GJ was kept for comparison of the results of the November 2009 version of EFDA-TIMES with later versions, see Section 5.6.
Test of the full supply chain for all end-use heat technologies – comparing EFDA TIMES and TIAM: Completion of cost and efficiency parameters for the following heat chains – from space heating demand to primary energy - Biomass, Oil burner, Gas burner, Electricity heating, Heat pump, District heating (small-scale and large-scale).	See Table 6.2. Technology chain for residential heat. The same method can be used for other technology chains, see e.g. Table 6.3. Technology chain for distributed electricity.
More detailed representation of heat and electricity infrastructure: Disaggregation of large-scale CHP (different efficiency factors for 'virtual heat pumps' and different technologies – gas, coal (with or without carbon capture and storage technologies - CCS), geothermal, fission (Generation III and IV), fusion.	Parameters for large-scale CHP are explained in Section 5.3..
Infrastructure - network and storages for intermittent electricity generation: Introducing national transmission grids, pumped storages, compressed air energy storage (CAES), international supergrids etc. (e.g. connecting desert solar electricity generation with markets).	This issue has been addressed in recent studies using the Pan European TIMES model. Technologies and parameters for the EFDA-TIMES model may be selected from these results, see Section 6.1.2
Scenarios: Similar to those presented in WP 2010 (Base Case, Nuclear fission constrained, infrastructure added). Presentation of results for global aggregation and selected regions.	See Sections 5.4, 5.6 and 5.8.
Introduction of the Myopic Variant (additional): Selected scenario will be calculated using the *myopic" variant of the TIMES model generator.	The use of the myopic variant is described in Section 5.9 with selected results..

1.3 Conference contributions and 'Virtual Conference Room'

The following contributions to workshops and conferences are based on the contributions to Workprogrammes 2010 and 2011:

- Modelling CCS, Nuclear Fusion, and large-scale District Heating in EFDA-TIMES and TIAM, *Poul Erik Grohnheit, Systems Analysis Division, Risø DTU,* *ETSAP Semi-annual Workshop, Cork, Ireland, 15-17 November 2010. File ETSAP_Cork_Grohnheit_v2.pdf (www.iea-etsap.org)*

- Long-term modelling of Carbon Capture and Storage, Nuclear Fusion, and large-scale District Heating, *Poul Erik Grohnheit, Søren B. Korsholm, Mikael Lüthje, Risø International Energy Conference, 10–12 May 2011, Files Risoe_2011_Fusion_CCS_Final.doc 04-04-2011 and Conference presentation Risoe_Conference_Final.ppt 10-05-2011.*
- Input documentation for ETSAP-TIAM and EFDA. *Poul Erik Grohnheit, Workshop for ETSAP-TIAM Collaboration, Sophia-Antipolis, France, 15 February 2012. File TIAM_RISOE_20120215.pdf.*

A 'virtual conference room' in Adobe Connect under the Danish Research Network was established for preparation of the workshop at Garching in December 2010 and used for later communication. The 'File Share' 'pod' of this virtual conference room contains the following files for download:

- *ETM_EFDA_1103.xls 01-05-2011* – documentation of scenario runs using versions ETM_0912, ETM_1011 and ETM_1103 with objective values for components and regions.
- *ETM_0912_BY_diff.xlsx 16-05-2011* – documentation of the differences of Base-Year templates (Base.dd files for GAMS) between ETM_1103 and ETM_0912.
- *Changes-Rev_3_Input_diff.xls 16-05-2011* – merge of EFDA-TIMES change logs since December 2005, etc.

1.4 Report Contents

The aim of this report has been to create a robust framework for addressing the issues listed in the Workprogramme 2011 and similar issues addressed in the previous workprogrammes. Most effort have been devoted to the selection of scenarios that may be used as a basis for analysing the impact of new technologies, their topology, and variations in key parameters together with a comprehensive presentation of model assumptions and results. In addition, this report contains a more technical presentation of the issues presented at workshops and conferences containing results of analyses using the EFDA-TIMES and similar global models.

Chapter 2 summarises techno-economic data for the selected fossil technologies. *Chapter 3* summarises resources and CCS storage potentials in the current EFDA-TIMES model. *Chapter 4* describes the search for a background scenario with selected results from EFDA-TIMES December 2009 version. *Chapter 5* describes the issues for introducing endogenous infrastructure for electricity, natural gas and heat within regions. *Chapter 6* discusses the topology and data for selected technologies in EFDA-TIMES and ETSAP-TIAM, emphasising technologies that need further development. *Chapter 7*, describes documentation of input data and comparison of different versions of TIMES models. Finally, *Chapter 8* contains the contribution to the annual report 2011 of Association Euratom – DTU with conclusion and presentation of the work in this report.

2 Data for fossil technologies

In EFDA-TIMES non-conventional oil and gas production is implemented as processes for extraction with an additional potential and higher costs compared to conventional production.

2.1 Non-conventional oil and gas production

The IEA Implementing Agreement Energy Technology Systems Analysis Program s (ETSAP) provides the ETSAP TECHDS Energy Technology Briefs to support the construction of technologies for the MARKAL/TIMES model family.

The brief for unconventional oil and gas resources (latest version May 2010) includes:

- Extra heavy oil (oil with high viscosity and API gravity of less than 10°.);
- Oil sand (sand containing bitumen);
- Oil shale (sedimentary rock containing kerogen);
- Tight gas (natural gas with low permeability);
- Coal bed methane (CBM, natural gas associated with coal);
- Shale gas (nat. gas associated with shale oil)
- Natural gas hydrates (structures of water ice trapping natural gas).

Production of unconventional oil is an energy intensive process that requires significant amounts of heat. Performance, costs and resources are summarised as:

- The energy used as a percentage of the energy produced range from 20-30 % for extra heavy oil, oil sand and oil shale, as compared to 6 % for conventional oil and gas.
- Associated CO_2 emissions range from 9.3 to 15.8 g/MJ for oil sand and extra heavy oil, and from 13 to 50 g/MJ for oil shale - with natural gas the most common fuel used for heating purposes during production
- Production of tight gas, CBM and shale gas involves lower emissions compared to unconventional oil due to lower energy requirement.
- The production cost of extra heavy oil and oil from sand ranges from \$6.6 to \$13.1/GJ. Oil from oil shale is more costly and ranges from \$8.2 to \$19.7/GJ. As a comparison, the cost of conventional oil ranges typically between \$1.6 to \$6.6/GJ, with some exceptions
- Production costs of unconventional natural gas range from \$2.6 to \$8.6/GJ for tight gas, CBM, shale gas, and natural gas from hydrates, compared to the range from \$0.5/GJ to \$5.7/GJ, for new conventional natural gas resources.
- The total estimated unconventional oil resources were 8-9,000:bbl by the end of 2005

- The total estimated unconventional gas resources were some 900 tcm for tight gas, CBM and shale gas, and between 1000 and 5000 tcm of natural gas from hydrates.

Unconventional oil and gas will hardly appear as fuels for electricity generation in the EFDA-TIMES model results.

2.2 Data for CCS and Biomass in EFDA-TIMES

The current version of EFDA-TIMES contains four biomass technologies and six CCS technologies with different types of CO_2 removal, cf. Table 2.1, which is an extract from Cabal and Lechón, 2009 (Table 16. Power generation technologies technical and economic data).

Table 2.1. Power generation technologies technical and economic data

Technology	Start	Efficiency*)	Availability	Life	Investment (M€/GW)		Fixed O&M (M€/GW)		Variable O&M (M€/PJ)	
					min	max	min	max	min	max
Biomass: Gasification	2003	0.38	0.85	25	1980	4340	30	130	2.28	4.10
Biomass: Combustion	2003	0.25	0.9	30	1980	3080	48	80	0.42	0.70
Biogas: Waste	2003	0.36	0.95	20	4320	8260	29	59	0.60	1.00
CHP: Biomass	2003	0.25*	0.9	25	2160	3360	42	70	0.42	0.70
CCS: IGCC+ CO_2 removal from input gas	2010	0.4	0.9	30	1755	2730	45	75	1.20	2.00
	2030	0.47	0.9	30	1206	1876	30	50	1.20	2.00
	2050	0.55	0.9	30	1305	2030	30	50	1.20	2.00
CCS: IGCC+ CO_2 removal from flue gas	2010	0.4	0.9	30	1890	2940	45	75	1.40	2.34
	2030	0.47	0.9	30	1296	2016	30	50	1.40	2.34
	2050	0.55	0.9	30	1395	2170	30	50	1.40	2.34
CCS: Pulverized coal + CO_2 removal from flue gas	2010	0.33	0.9	40	1980	3080	51	85	0.84	1.40
	2030	0.44	0.9	40	1710	2660	45	75	0.84	1.40
	2050	0.48	0.9	40	1440	2240	45	75	0.84	1.40
CCS: NGCC + CO_2 removal from flue gas	2010	0.5	0.9	30	1080	1680	18	30	1.94	3.23
	2030	0.58	0.9	30	900	1400	12	20	1.94	3.23
	2050	0.65	0.9	30	765	1190	12	20	1.94	3.23
CCS: SOFC gas	2020	0.44	0.85	15	1354	2106	18	30	1.20	2.00
	2040	0.67	0.85	15	990	1540	12	20	1.20	2.00
CCS: SOFC coal	2030	0.46	0.9	15	1800	2800	30	50	1.20	2.00
	2050	0.6	0.9	15	1395	2170	30	50	1.20	2.00

*) Efficiency in CHP plants refers to electricity efficiency only

These data represents the State of the art for EFDA-TIMES and TIAM.

The biomass technologies are obsolete or current technologies with low efficiencies for power generation. Already available and future more efficient vintages are not considered in this version of the model. This should be improved in the next versions.

In contrast, the CCS technologies are all future technologies with increased efficiencies and lower costs until 2050. Oxyfuel technologies, which are included in the Pan-European TIMES model are not considered.

2.3 Heat recovery by industry or large district heating systems

The various TIMES models contain techno-economic parameters that quantify expectations on gradually increased efficiencies and lower costs during the next 3-4 decades. The most critical parameter is the loss of thermal efficiency during carbon capture. For example, the efficiency of modern coal-fired steam turbines (pulverised coal) will be reduced from 46 % to 36 %. This will improve in the future for both with and without CCS, and for some of the variants of CCS technologies the difference may be reduced. Table 2.2 shows the assumptions chosen for quantitative modelling in the Storage Utsira project.

Table 2.2. Efficiencies for new large gas and coal fired power plants and the same technologies with CCS.

		2010	2020	2030	2040
Reference plants	NGCC	58.0	60.0	63.0	64.0
	PC	46.0	50.0	52.0	52.0
	IGCC	46.0	50.0	54.0	56.0
Post combustion, capture rate 85 %	NGCC	49.0	52.0	56.0	58.0
	PC	36.0	42.5	45.0	46.0
Pre combustion, capture rate 85 %	IGCC	38.0	44.0	48.0	50.0
Oxyfuelling plants, capture rate 94 %	NGCC	48.1	50.1	51.6	52.1
	PC	38.0	40.5	43.0	44.0

Source: Analysis of potentials and costs of storage of CO2 in the Utsira aquifer in the North Sea. WP2: Assessment and harmonization of CCS related economic and physical performance parameters of the MARKAL and TIMES models. Ric Hoefnagels, Andrea Ramírez Ramírez, Copernicus Institute for Sustainable Development and Innovation. Group Science, Technology and Society, January, 2010.

Although cogeneration technologies for both district heating and industrial processes has been a key issue for the MARKAL and TIMES models, the use of combined heat and power (CHP) has not been systematically studied together with CCS. Obviously some of the energy lost in the carbon capture process could be recovered for heat to supply large-scale district heating systems or industrial processes. Taking into account the infrastructure requirements for CCS with long-distance transport of captured CO_2 there are significant economies of scale when developing this technology. It means that small-scale CHP and distributed electricity, which works well with biomass, is not very interesting together with CCS.

3 CCS storage potentials

Figure 3.1 show the cumulative capacity of CO_2 storages in world regions. These capacities are highly uncertain.

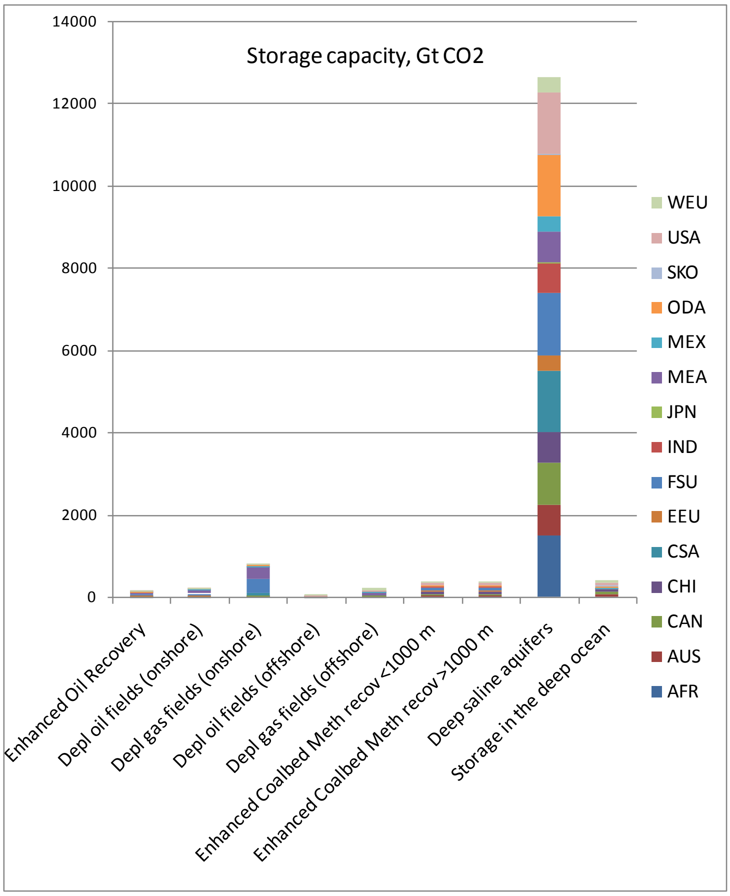


Figure 3.1. Cumulative CO_2 storage capacity,

In particular for Europe, there are various estimates for the carbon storage capacity. Very comprehensive analyses of the European storage potential, focussing on saline aquifers and hydrocarbon fields that have been done within European research projects. According to the most recent study, GeoCapacity the theoretical storage potential in Europe amounts to about 400 Gt CO_2. Assuming that not the total storage volume can be used effectively, GeoCapacity states a conservative estimate of about 120 Gt for Europe (here the EU-27 plus Norway, Switzerland and Iceland. Thereby 80 % are represented by saline aquifers, 17 % by hydrocarbon fields and 3 % by coal seam and Enhanced Coal Bed Methane recovery (ECBM), Table 3.1

In Figure 3.1 the capacity in WEU for the dominant resource, deep saline aquifers, is 375 Gt., which is similar to the theoretical potential in GeoCapacity, but several times the conservative estimate.

Table 3.1. Theoretical potential and conservative estimate for CO_2 storage in EU27+3.

	Theoretic / optimistic potential	Conservative estimate
Aquifers	342.0	94.3
Hydrocarbon fields	38.4	20.5
Coal seams / ECBM	23.9	3.1
Total (EU 27+3)	404.3	117.9

Source: Kober, Blesl, 2010

4 Scenario definitions

This chapter describes the search for a background scenario with selected results from EFDA-TIMES December 2009 version. However, a similar analysis using different versions of EFDA-TIMES may lead to different conclusions for the selection of background scenarios. The more recent versions of EFDA-TIMES did not identify scenarios with a measurable amount of CCS.

4.1 The Reference (BASE) Scenario

In the Base Scenario a carbon price, representative of a moderate concern about climate change, has been included; the scenario contains no incentives for CO_2 reduction at 2010 and a carbon price differentiated between OECD and non-OECD regions for the following periods. The carbon price gradually increases from 10 \$/tCO_2 in 2020 to 25 \$/t CO_2 in 2100 in non OECD regions and from 20 \$/T CO_2 to 50 in 2100 in OECD regions.

The electricity generation in the Base Scenario shows an annual growth rate of nearly 2.6% in 2000-2050 period and of 1.5% in 2050-2100. The growth of energy production in EFDA Base Scenario (31400 TWh in 2030) is very close to the Reference case of IEA's World Energy Outlook 2008 (33265 TWh in 2030). In the EFDA scenario electricity production grows up to 67300 TWh in 2050, and 105200 TWh in 2100.

Investment costs for LWR reports fission investment costs are those included in IEA ETP projections.

4.2 Electricity demand

Economic development is expected to increase all over in the world, although the rate of increase is very different in different world regions. Socio-economic development is captured in the model by a set of underlying drivers: population, number of households, GDP and GDP per person. Demands are a mixture of final energy demands, energy services and materials. The global demand for primary energy in the model increases from 383 EJ in 2000 to 844 EJ in 2050 and 1528 EJ in 2010. This demand increase in the model is high, but it is in line with other models (e.g. TIAM), and the per capita increase in primary energy is not implausibly high.

4.3 Scenarios to illustrate biomass and CCS

As shown in the sensitivity analyses focusing on fusion, constraints on CO_2 emissions will have the greatest impact on the fuel mix during the whole 21st Century. In contrast to all other technologies, which are competing mainly on the basis of their costs, fossil fuels with CCS will penetrate only when the emission constraint is effective.

All renewables – including biomass are – subject to resource constraints, which are effective in all regions and all periods, while the resource constraint for nuclear fission may not be effective until late in the century. This may lead to results with nuclear fission dominance far beyond public acceptance. A side effect of this dominance is that there is no room for fossil fuels with CCS. Thus, some kind of limit for nuclear fission will be necessary.

To avoid results with nuclear fission dominance far beyond public acceptance a conservative assumption will be that nuclear fission should not increase above 25 % of electricity generation each region during the rest of the century. In few regions (JPN, SKO and WEU) the share of fission was higher than 25 % in 2000 and maximum values are set in for 2010 in the Base Scenario, which is higher than generation in 2000. However, with increased demand for electricity, nuclear fission may increase in all regions after 2050, in absolute terms from 8.8 EJ (2,435 TWh) in 2000 to 45.5 EJ (12,645 TWh) in 2100.

Technically, this scenario (NucReg25) was made by calculating an absolute number that is the largest value of the limit for 2010 and 25 % of total electricity demand in each region and year. The first attempt was setting up a share constraint to be applied to each region and each period. However, this constraint gave very long and unpredictable solution times, e.g. from 15 minutes to more than 10 hours.

The scenarios selected to illustrate the role of biomass and CCS are summarised in Table 4.1, which also shows the variation of the objective value. The combination of the NucReg25 scenario and emission constraints leading to CO_2 concentration in the atmosphere at 550 ppm (Emi550) was chosen as the starting point for further sensitivity analyses (Grohnheit, 2010a)..

Table 4.1. Scenarios selected for analysis of CCS.

	Objective value			Core scenario=100		
Selected Scenarios	Base	Emi550	Emi450	Base	Emi550	Emi450
Base	186895			99.1		
NucReg25	187031	188627	193604	99.2	100.0	102.6
Biomass_High, CCSminus		188540			100.0	
Eplus		209085			110.8	
Demand20		174053			92.3	

The difference in objective value between the Core Scenario at 550 ppm and the nuclear fission constraint is less than 1 %.

The variants higher biomass potentials and “CCSminus”, assuming that investment costs for CCS technologies are 20% lower than in the base case, will reduce the objective value by less than 0.1 %.

In contrast, the more severe constraint on CO_2 emissions leading to CO_2 concentration in the atmosphere at 450 ppm (Emi450) gives the objective value that is 2.6 % higher than the Core Scenario.

Two additional scenarios were selected for this presentation:

- Eplus scenario – (representative of a growing concern about climate change): No incentives at 2010 in all region but WEU (10$/t$CO_2$) and a undifferentiated carbon price increasing from 50$/t CO_2 in 2020 to 200$/tCO_2 in 2100.
- Demand20 scenario in which the demand forecasts in the Base Scenario are reduced by 1 % every five years from 2000 to 2100. Thus, the demand forecasts are reduced by 10 % for 2050 and 20 % for 2100.

Figure 4.1 shows the global emission profile for the two scenarios Emi550 and Emi450.

The profile 550 ppm allows global CO2 emissions to increase to 33 Gt by 2030 and decrease to less than 20 Gt by the end of the century,, while the 450 Gt profile will already decrease from 28 Gt in 2015 to a level of 10 Gt during the last decades of the century. These profiles will have a significant impact on the technology choice..

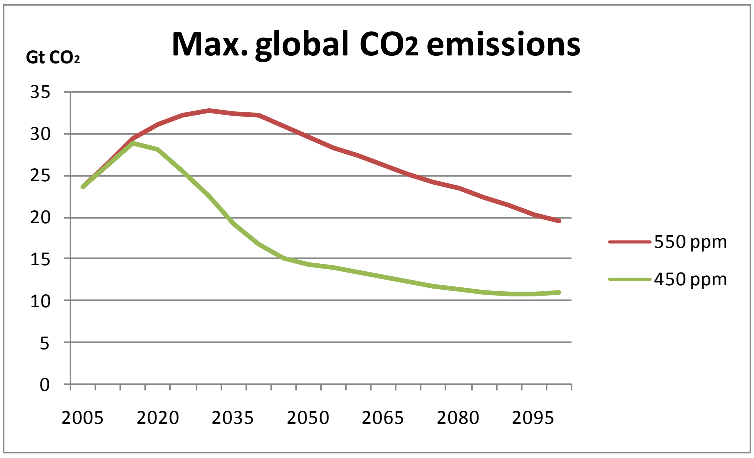


Figure 4.1. Global CO_2 emission profiles for the 450 and 550 ppm .

4.4 Global results for primary energy

In the Base Scenario no major constraints are applied. Only costs and physical resource limits count. Fossil fuels remain dominant – between 66 % and 75 % in the whole period. Coal production increases by more than a factor of 4, and coal remains a fuel that is consumed in the same region as it is produced – with little international trade. Gas production increases by a factor of more than 6, while oil will increase by little more than 50 %. Carbon emissions go up considerably. Hydro is gradually increasing. Fusion is not applied in this scenario, nor are renewable energies playing a major role. Biomass and waste will increase by less than factor 2. Nuclear fission sees large growth over the century but remains much less than coal.

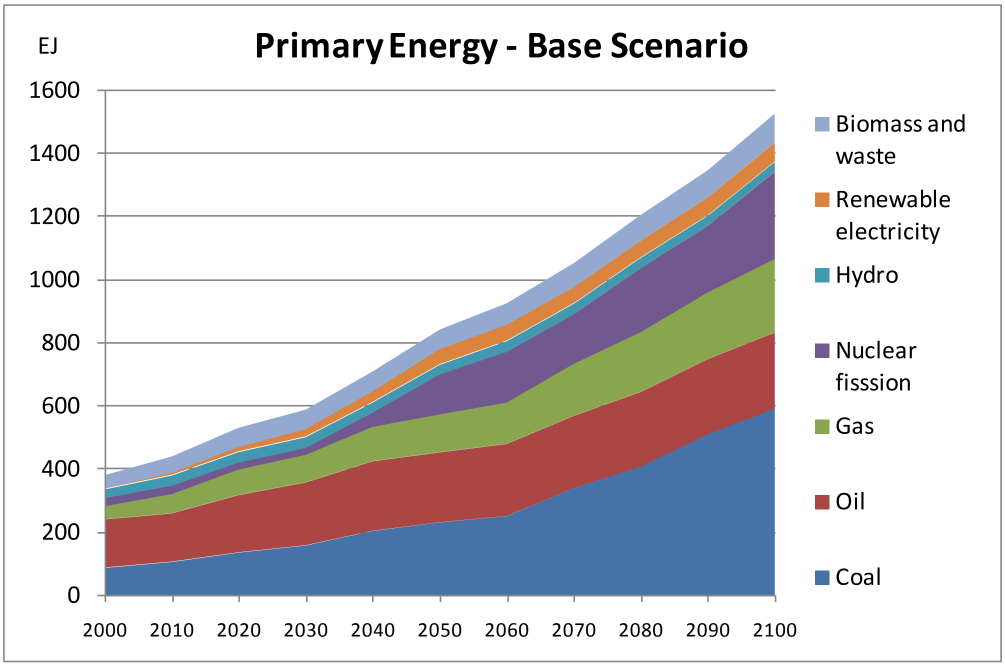


Figure 4.2. Primary energy in Base Scenario

Consistent with many energy scenario models, a world which has a strong increase in electricity and primary energy demand but which does not care about CO_2 emissions is expected to return to coal as the central primary energy source. In such a world coal is expected to supply a large fraction of the primary energy in 2100 with associated impacts on emissions and final energy carriers. Nuclear fission is also expected to play an important role in the electricity sector.

4.5 Global results for electricity

Coal is even more dominant in the electricity sector with about half of the electricity generation in the last three decades of the century followed by nuclear with one-fourth from about 2050 The fraction of fission increases only in the second half of the century, and it is pulled into the market by the large demand growth primarily in developing countries, see Figure 4.3.

Total power generation will increase from 52 EJ (14,000 TWh) in 2000 to 184 EJ (53,000 TWh) in 2050 and 383 EJ (106,000 TWh) in 2100. As expected the increase in power generation by a factor of more than 6 is larger than the increase in primary energy by factor 4.

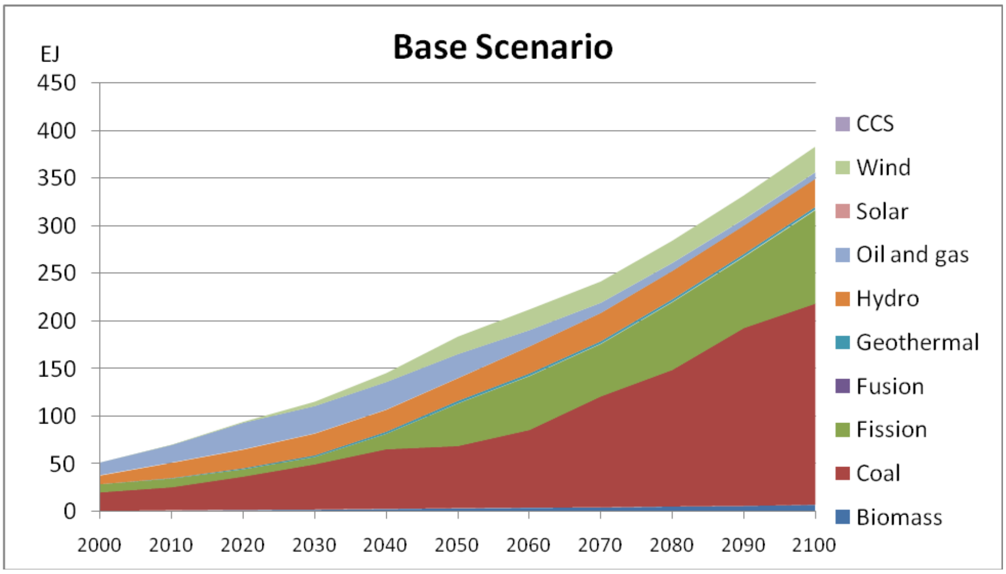


Figure 4.3. Power generation, Base Scenario.

In the additional scenario used for this study focusing on CCS and biomass, nuclear fission is constrained to maximum 25 % in each region. Although the global share of nuclear fission exceeds this constraint by small amounts in some years, this will reduce the global amount of nuclear fission to 18 % or less, which is about the nuclear share of power generation in 2000. Even without any constraint on CO_2 emissions, this means that fusion enters into the solution by a small, but increasing amount the end of the century, up to 5 % of total power generation in 2100. Fusion will be selected by the model by a small amount for Mexico, a significant share for India and Japan, and with a very dominant role in South Korea, which replaces the total dominance of fission in the Base Scenario for South Korea.

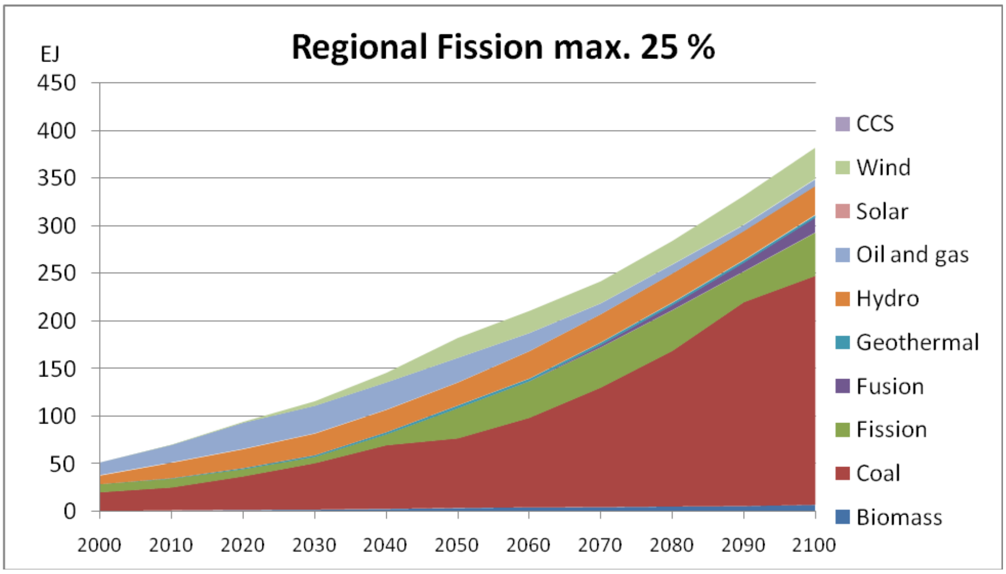


Figure 4.4. Power generation: Max. 25 % nuclear fission in each region

The picture looks completely different when CO_2 emissions are required to reduce strongly. In such a world, technologies with no or only low CO_2 emissions start to dominate. Fusion is one of these technologies. In the modelling here there is found to be a very large role for nuclear fission, renewables (particularly wind and hydro) and for fusion, if available. In scenarios explored so far, the role for CCS technologies tends to be lower by the end of the period, in part because the capture technologies are assumed to be only 90 % efficient. However, in the period before fusion is able for take-off, CCS can play a significant role – up to 11 % of the global power generation in 2060-2070 – as a contribution to bridge the gap between a fossil dominated energy system and a large contribution from fusion. Figure 4.5 shows the global electricity production in a carbon constrained scenario equivalent to restricting the atmospheric CO_2 concentration to 550 ppm (equivalent), which is chosen as the Core Scenario for further sensitivity analysis.

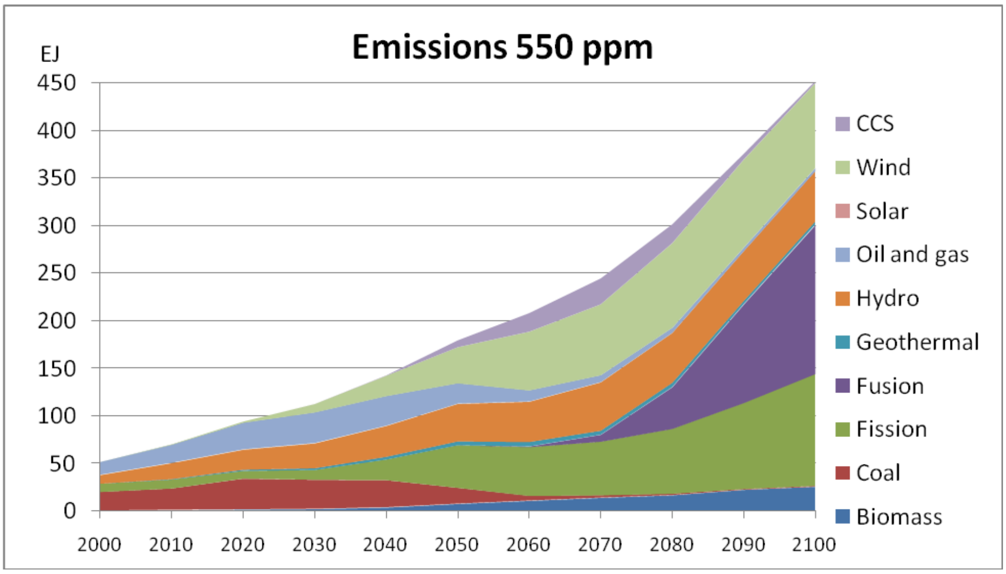


Figure 4.5. Power generation, Core Scenario: Emission reduction 550 ppm.

The first variant to the Core Scenario is the stricter constraint on emissions equivalent to restricting the atmospheric CO_2 concentration to 450 ppm. The most significant change compared to the 550 ppm scenario is that electricity generation increases from 451 EJ in the Core Scenario to 479 EJ. This is explained by a substitution from direct use of fossil fuels to electricity, which is more suitable for emission reduction. The most significant change in the technology mix is before 2050 – with much less fossil fuels and more biomass, geothermal and CCS. In both scenarios wind power and nuclear fission become very important in the second half of the century, but starts earlier in the 450 ppm scenario. Also fusion will have a larger share in the 450 ppm scenario.

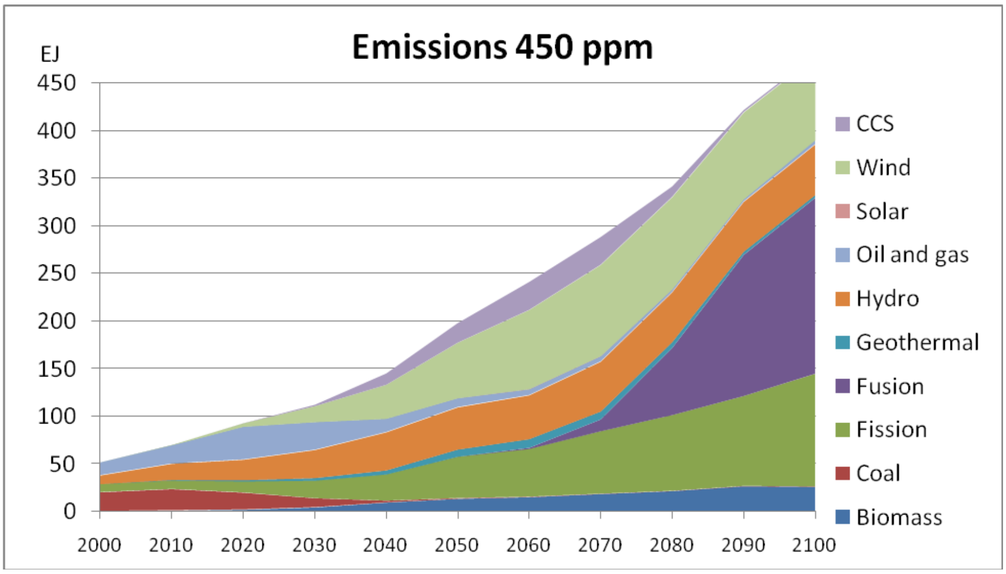


Figure 4.6. Power generation, Core Scenario variant: Emission reduction 450 ppm.

4.6 Global results for CCS

As shown in Figure 4.5 for the "Core Scenario" with emission reduction to 550 and nuclear fission constrained to maximum 25% of the electricity generation in each region CCS technologies are selected in the mid-century, CCS can play a significant role – up to 11 % of the global power generation in 2060-2070 – in the selected scenarios as calculated by the EFDA-TIMES, December 2009 version. Figure 4.7 is zooming into the CCS results in Figure 4.5, showing the regional output from all CCS technologies. The maximum global output is 27 EJ in 2070, which is dominated by China and India.

However, in the period before fusion is ready for take-off, CCS can play a significant role – up to 11 % of the global power generation in 2060-2070 – as a contribution to bridge the gap between a fossil dominated energy system and a large contribution from fusion.

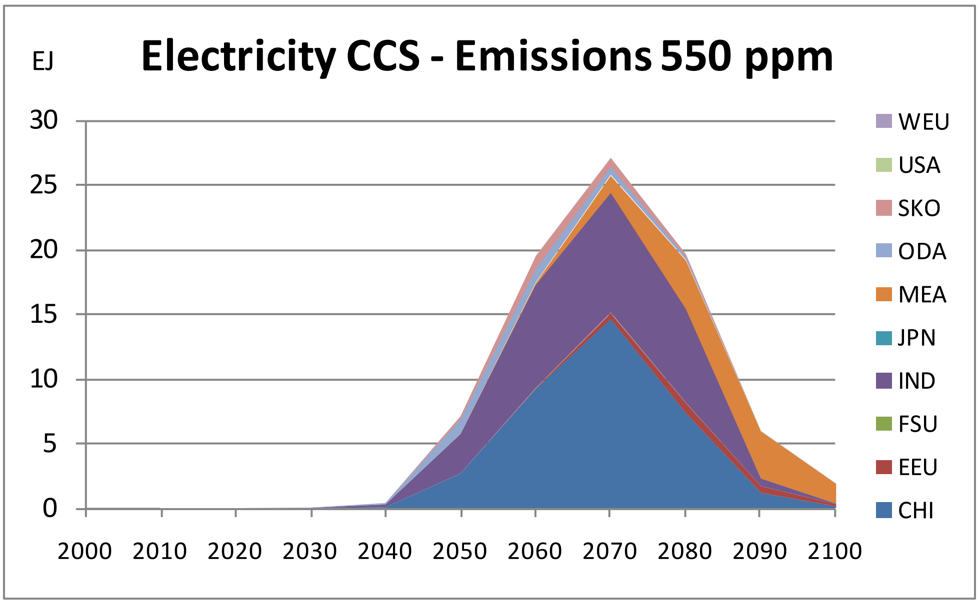


Figure 4.7. Regional output from all CCS technologies, Emission reduction 550 ppm..

Figure 4.8 shows the same story for the 450 ppm scenario, zooming the CCS section of Figure 4.6. The global output will reach the maximum 29 EJ already in 2060, The result for 2070 is similar to the 550 ppm scenario, but after 2070 the reduction is faster.

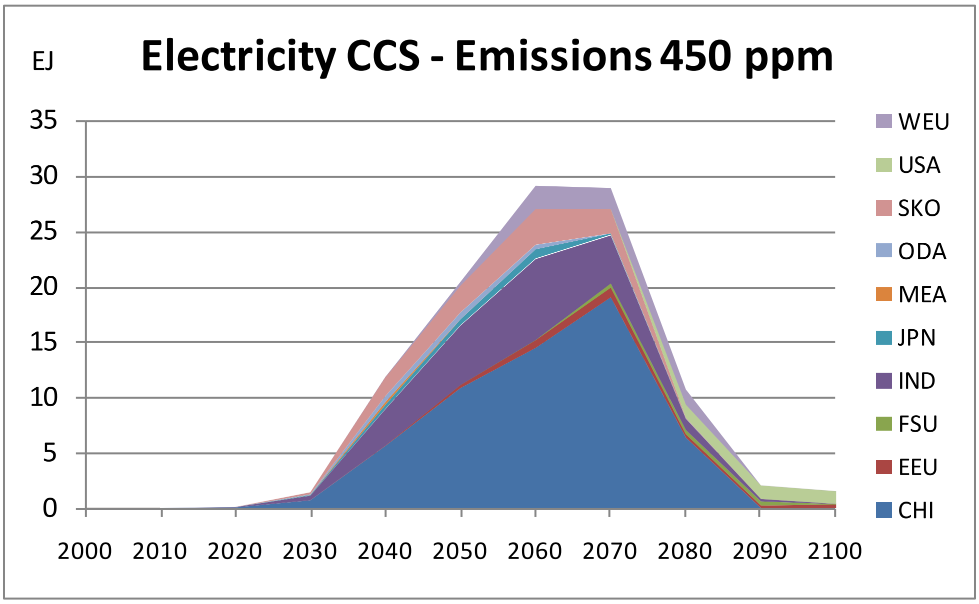


Figure 4.8. Regional output from all CCS technologies, Emission reduction 450 ppm.

Figure 4.9 shows that natural gas combined cycle with CCS vintage 2050 is the dominant technology in the 550 ppm scenario, while Figure 4.10 shows that a variety of technologies is selected in the 450 ppm scenario. In the 550 ppm scenario natural gas combined cycle (NGCC) is the dominant technology. The 2030 vintage of the model will be chosen in a very small amount, while later the 2050-vintage becomes dominant.

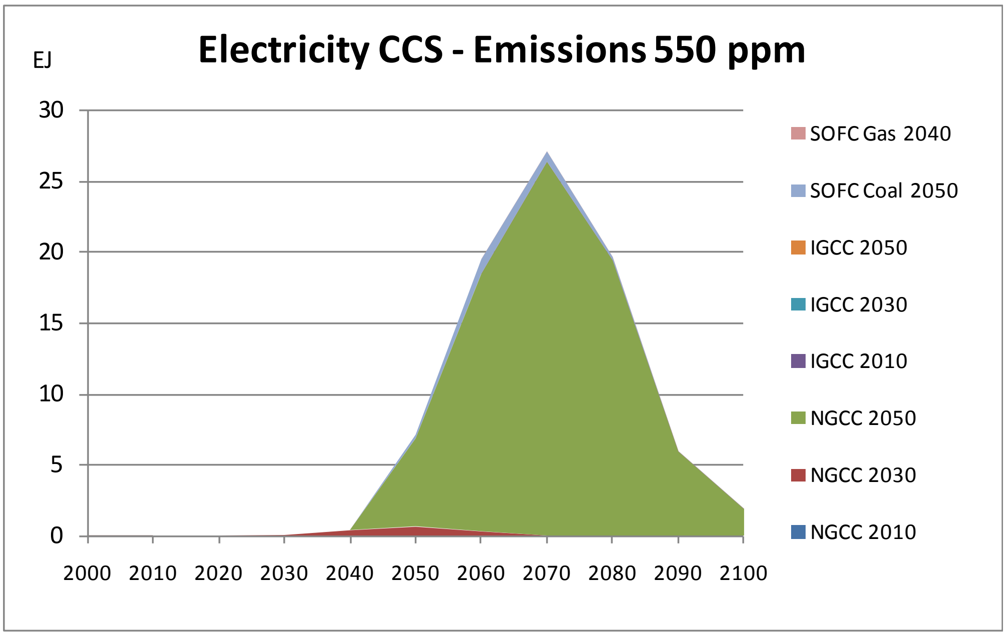


Figure 4.9. Global output from CCS technologies, Emission reduction 550 ppm.

Figure 4.10 shows similar results for the 450 ppm scenario. A larger variety of natural gas based technologies become dominant, and also fuel cells are selected by the model.

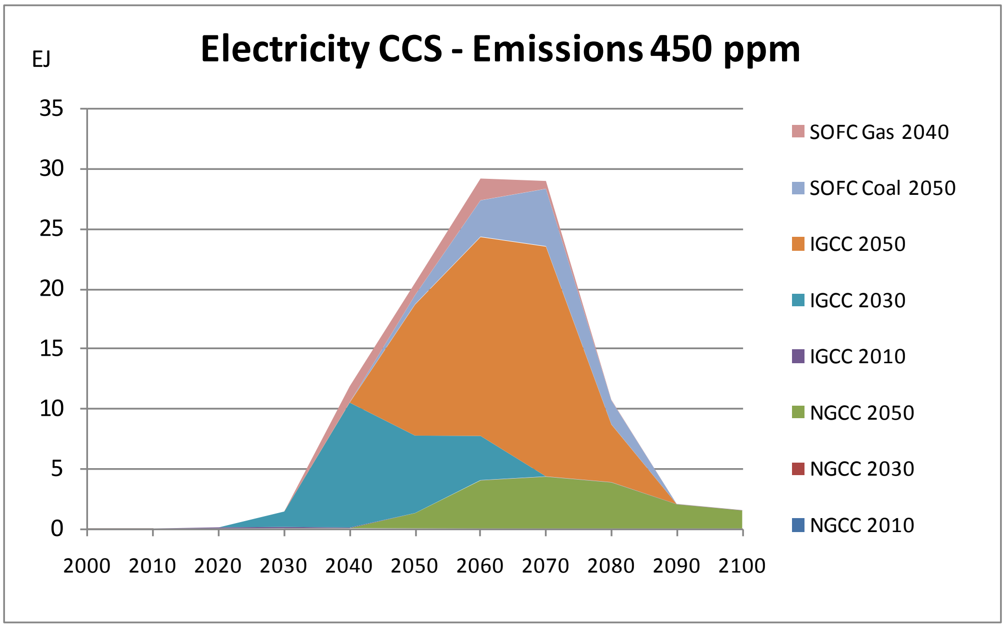


Figure 4.10.Global output from all CCS technologies, Emission reduction 450 ppm.

4.7 Results for endogenous heat transmission

Endogenous heat transmission is introduced in Figure 4.11. The global market for electricity in 2090 is 376 EJ; fusion is 2 EJ larger in 2090 when heat transmission is available, but the pattern of the global electricity supply is unchanged. On the global level it is little impact on the technology choice for electricity generation, given the assumptions in the model. Thus, Figure 4.11 is very similar to Figure 4.5.

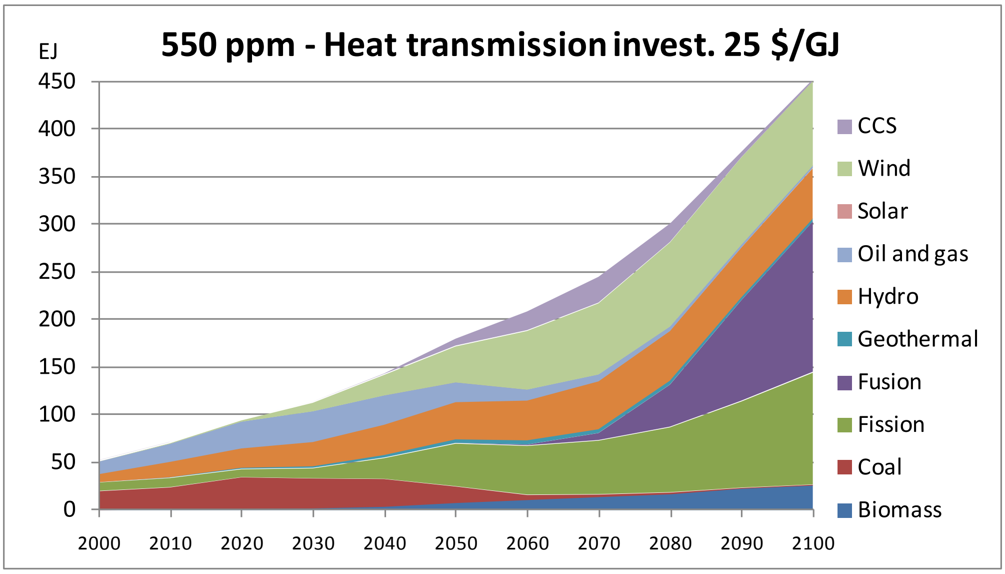


Figure 4.11. Power generation, Emission reduction 550 ppm with endogenous heat transmission.

The global market for heat is 24 EJ in 2090. While the impact of heat transmission for choice is very limited in the current model versions, it may have a significant impact on the technology choice for heat. This is illustrated when comparing Figure 4.12 and Figure 4.13. Transmission and distribution of heat from large power stations to urban areas has a very large potential, in particular by the end of the century with continuously expanding urban areas, in particular in China. In the results shown here. heat transmission will mainly replace geothermal heat. However, much further development of the model will be needed, as discussed in the next chapter.

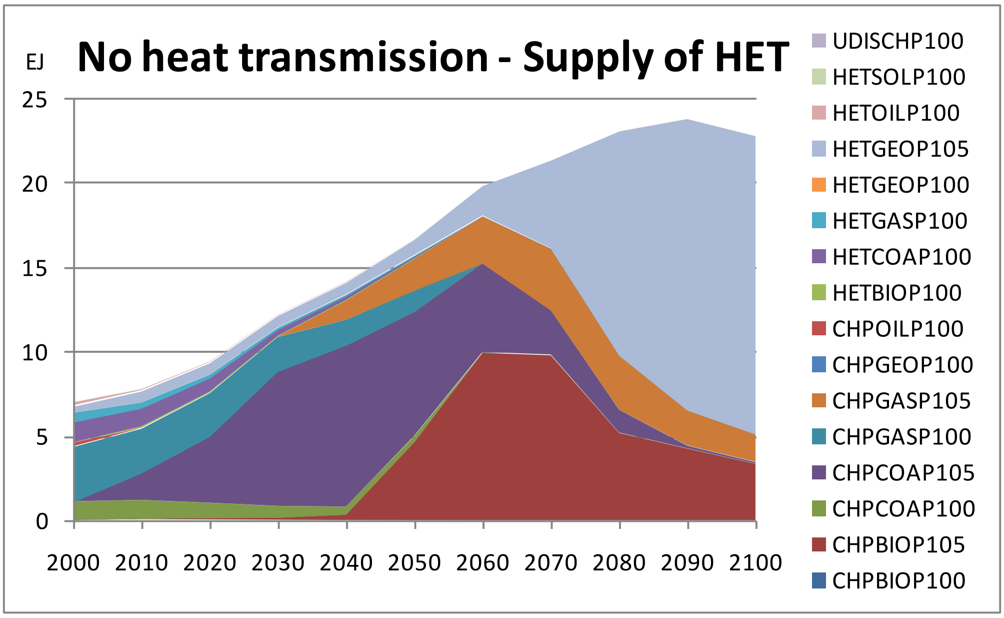


Figure 4.12. Technology input for heat. Transmission process not available.

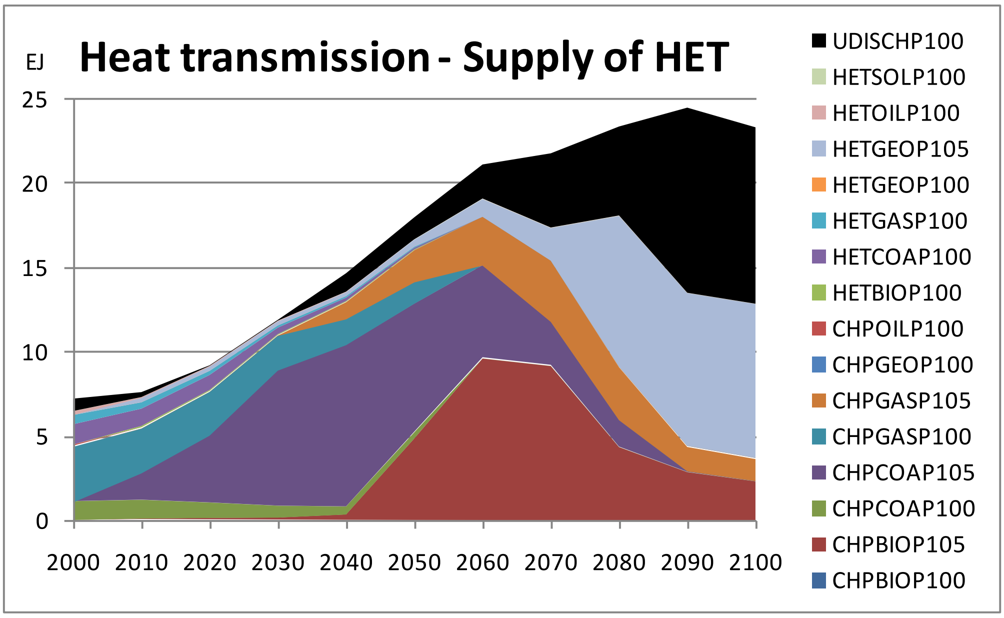


Figure 4.13. Technology input for heat with transmission process.

4.8 Conclusion on CCS in the selected scenarios

CCS is one of the technologies which have been anticipated to play a role if there are significant restrictions on global carbon. However, the maximum penetration observed in any scenario without an effective limit on the share of nuclear fission is very small, about 6 % in a scenario with emission constraints equivalent to 650 ppm (Han and Ward 2010). This appears to be partly because CCS is not an entirely carbon-free option (only 90 % of the CO_2 is captured), hence even though it is carbon constraints which drive the introduction of CCS technologies, tight carbon constraints tend to exclude CCS.

In a study by TIAM focusing on dominance of renewables and severe constraints on all nuclear technologies, CCS will play a very important role from 2020 or 2030 and the rest of the century (Føyn et al., 2010).

CCS is a technology with a more temporary role, which may be needed to bridge the gap between the current energy system dominated by fossil fuels and a future system based on renewables and nuclear fusion. The highest penetration of CCS is found in the period 2050-2070, and the penetration seems very sensitive to variations in costs of CCS, as shown by the scenario with 20 % reduces investment costs for CCS.

However, the model results for CCS is very sensitive to the whole set of scenario assumptions.

5 Modelling infrastructures

Introducing endogenous infrastructure for electricity, natural gas and heat within regions will better allow a proper modelling of technologies that require piped transmission and distribution of energy carriers. Each grid is defined in the topology by commodity flows in and out, efficiencies (losses), and investment and O&M costs per GJ of annual flows. However, these parameters are very aggregated, and their numerical values can be selected only as a result of systematic parameter studies.

5.1 Heat distribution infrastructure supporting old and new technologies

Fossil fuel plants with CCS and heat recovery may be a driver for the development and expansion of large-scale district heating systems, which are currently widespread in Northern and Eastern Europe, Korea and China, and with large additional potentials in North America. These systems need several decades for development, mainly by interconnection of existing smaller grids. If fusion will replace CCS in the second half of the century, the same infrastructure for heat distribution can be used, which will support the penetration of both technologies.

In addition, district heating systems with CHP and heat storages offer some of the flexibility in electricity generation that is required for wind power and other intermittent electricity generation.

In contrast to current nuclear fission with light water reactors, which operate at relatively low temperatures, the steam parameters for fusion – with temperatures in the range 600-800ºC – are similar to advanced coal or combined cycle gas turbines. This is suitable not only for CHP, but also other types of co-generation, e.g. catalytic hydrogen generation.

5.2 EFDA-TIMES with large-scale CHP

Cogeneration or combined heat and power (CHP) is a very important technology in technology-rich energy flow optimisation models that are used to model the mix of technologies to meet future demands for energy services or materials from energy intensive industrial processes.

The network for transmission and distribution of electricity is a mature infrastructure all over the developed world. The networks are difficult to model without a detailed geographical representation, so the further development of this infrastructure may be neglected in these models. Investments in new electricity transmission network is needed mainly to support large-scale deployment of resource-dependent technologies, e.g. hydro power, solar power located in deserts or wind power. Existing grids for large-scale heat transmission only exist in few city regions supplies by urban waste incineration and fossil fuel CHP plants, so further expansion of large-scale CHP also requires investments in district heating grids, except for industrial CHP.

In some multi-regional TIMES models trade between regions is modelled by transport costs and capacity limes of pipelines or interconnectors, but trade within regions can be made only for grids that are aggregated into a single point, to which costs and capacity limits are assigned.

To model district heating supply from large power stations it is necessary to introduce heat transmission as a technology for endogenous investment assuming a flow efficiency and cost (investment and annual operation) per unit of annual flow. Preliminary model runs show that investment cost in the range € 25-50 per GJ annual flow will lead to results that may be used to illustrate the competition among heat supply options.

5.3 Parameters for large-scale CHP – virtual heat pumps

To understand the cost of electricity and heat from cogeneration and the impact of the recent technical development it is necessary to describe a set of techno-economic parameters, which are derived from the thermodynamics of generation of electricity.

Figure 5.1 shows the operating area for CHP units. Back-pressure units produce along the back-pressure line. Extraction-condensing unit produces within the maxima and minima for power and heat. The vertical axis represents condensing (electricity-only) capacity.

The iso-fuel line describes the power-loss ratio. A typical value for both traditional and modern units is c_v*=0.15*. Typical values for the power-heat ratio are c_m*=0.5* for a traditional gas turbine, c_m*=0.7* for a large modern extraction-condensing unit, and c_m*=1.0* or more for a modern combined-cycle gas turbine for decentralised CHP.

Figure 5.1 usually describes the operation area for electricity and heat production in individual extraction-condensing units. For decades these units in the capacity range 250-500 MW have been the most important type of electricity generating units in Denmark, which have been systematically located at the heat distribution grids of the larger cities. (Grohnheit, 1993).

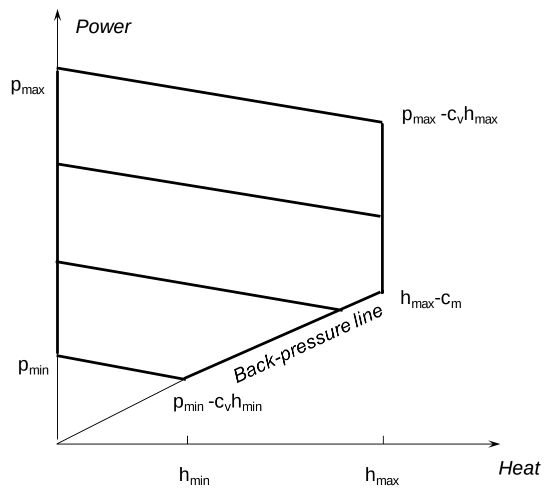


Figure 5.1. CHP parameters

However, for modelling purposes the figure can represent an aggregation of units serving a national electricity system and aggregations of district heating systems, using a set of constraints on heat flows in time-slices (i.e. seasonal and diurnal break-downs of the year). The coupled production of aggregated electricity and heat may be flexible within certain limits, in particular to meet increasing electricity demand or reduced wind production. The reduced heat supply to the district heating system can be met by peak-load boilers or heat storages.

A further interpretation of the parameters in Figure 5.1 is to consider heat production by CHP as a virtual heat pump. It means that part electricity generated in condensing mode is converted into heat at an efficiency factor that is the inverse of the power-loss ratio. Instead of operating a physical heat pump by electricity, part of the steam in the turbine is sent to a heat exchanger and the district heating network rather than the low-pressure turbine and the power generator.

Interpreting CHP as virtual heat pumps makes it much easier to integrate CHP and heat supply from power stations with CCS into a heat market, where also individual heat pumps become increasingly important (Grohnheit, 2010b). The various heat supply technologies will compete on efficiencies, fuel price and requirement for investment in house installation as well as city-wide infrastructure.

Table 5.1. CHP as "virtual heat pumps"

Technology	Power-loss-ratio	Efficiency factor
Electricity driven heat pump	n.a	3
Nuclear CHP	0.25	4
Coal/gas CHP; Fission Gen. IV and Fusion.	0.15	7
Low-temperature DH	n.a.	10
Conservative average for heat transmission	n.a.	5
CCS with heat recovery	n.a.	n.a.

5.4 Model results from EFDA-TIMES

In the latest work programmes of EFDA-TIMES the work has focused on sensitivity analyses. One of these analyses was aimed at identifying combinations of assumptions that will allow biomass and CCS to play a significant role by 2050 and later (Grohnheit, 2011). Figure 5.2 shows selected results from this analysis. The presentation is limited to Europe, which is the sum of the EFDA-TIMES regions WEU and EEU. In addition to the Base Scenario, an scenario combining constraints on the share of nuclear fission (maximum 25% of electricity generation in each region) and the global limit of CO_2 emissions to 450 ppm. The latter constraint is applied for numerous scenario analyses.

Electricity supply

Heat supply

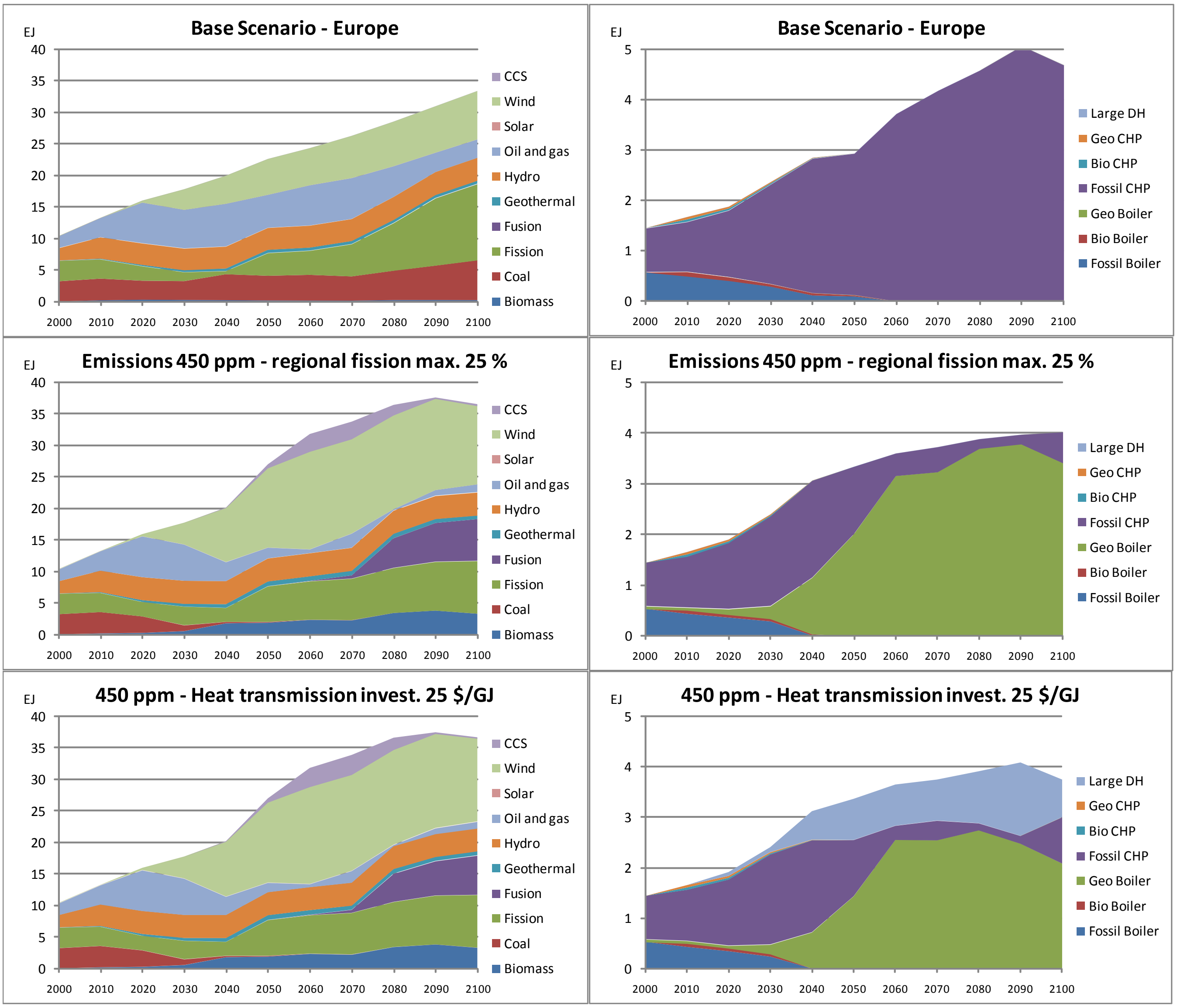


Figure 5.2. EFDA-TIMES results for electricity and heat supply in Europe 2000-2100. Base Scenario and two scenarios with emission constraints.

An additional scenario is added introducing a technology that represents the heat transmission and distribution infrastructure using a very aggregate parameter for investment costs at 25 $/GJ annual flow. The choice of investment cost is based on a parameter study, showing that the infrastructure technology would not enter into the solution at much higher costs.

Without further modification of the model the results for the electricity supply (Figure 5.2, left) shows the option for large scale heat supply by has little impact on the mix of electricity supply. However, there is a measurable increase in fossil generation with CCS.

In contrast, the impact on the mix of heat supply technologies is more significant (Figure 5.2, right). Large-scale district heating enters into the solution from about 2020. Geothermal heat becomes the dominant technology for heat supply in the model results when CO_2 is constrained to 450 ppm. However, this technology is very dependent on infrastructure matching geothermal resources and the market for heat at 100-200 ºC. So far, this infrastructure has not been considered in the model development.

Focusing on the electricity generation mix the further presentations of results will be based on only the first and last case in Figure 5.2.

Globally, the increase in energy demand is much higher than for Europe, which will allow fusion to play a larger role by the end of the century, if left unconstrained. The global results, see Figure 5.3, are highly influenced by the huge growth in the large developing regions, China and India, see Figure 5.4 for China. These results show clearly that much more elaborate constraints are needed to reflect the physical structure and possible infrastructure development. This issue also applies for the TIAM model.

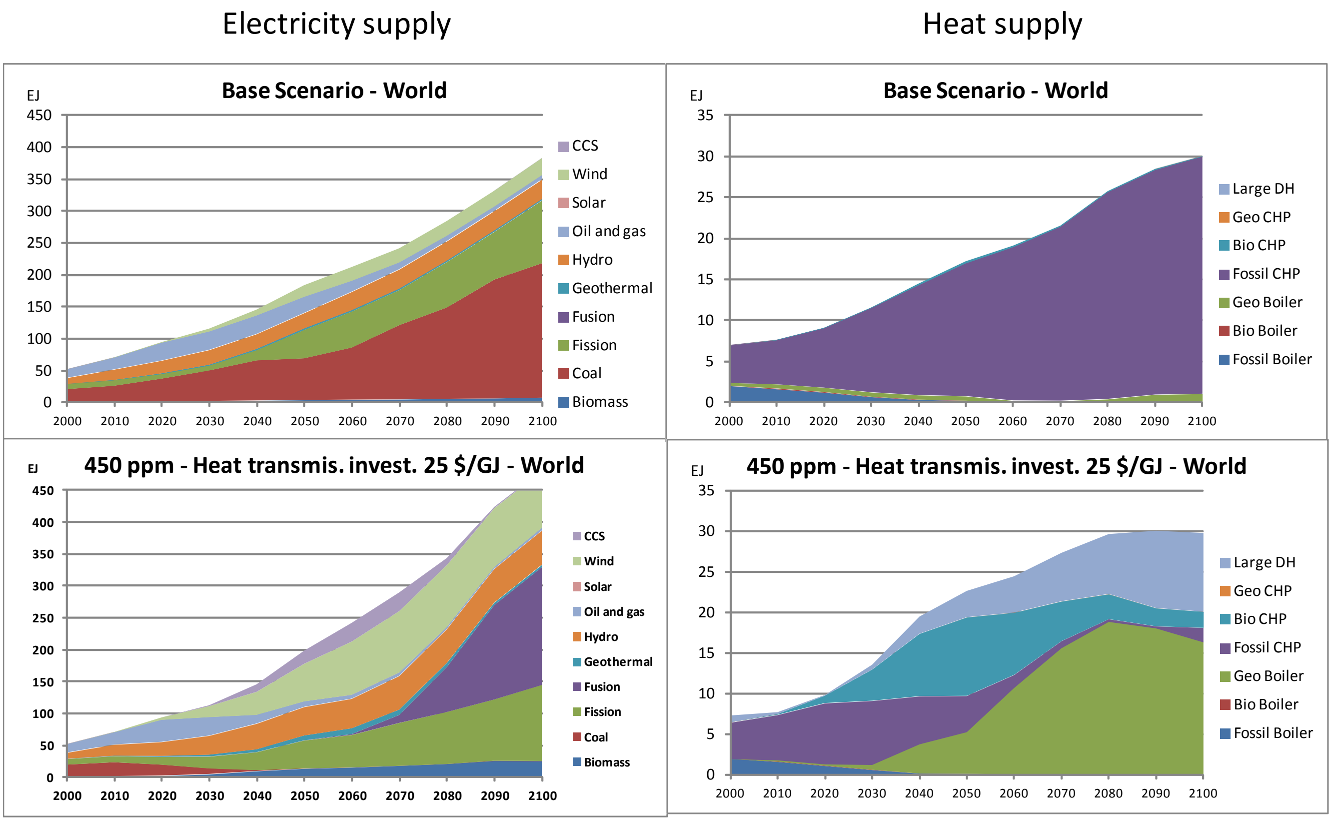


Figure 5.3. EFDA-TIMES results for electricity and heat supply in the world 2000-2100. Base Scenario and scenarios with emission constraints.

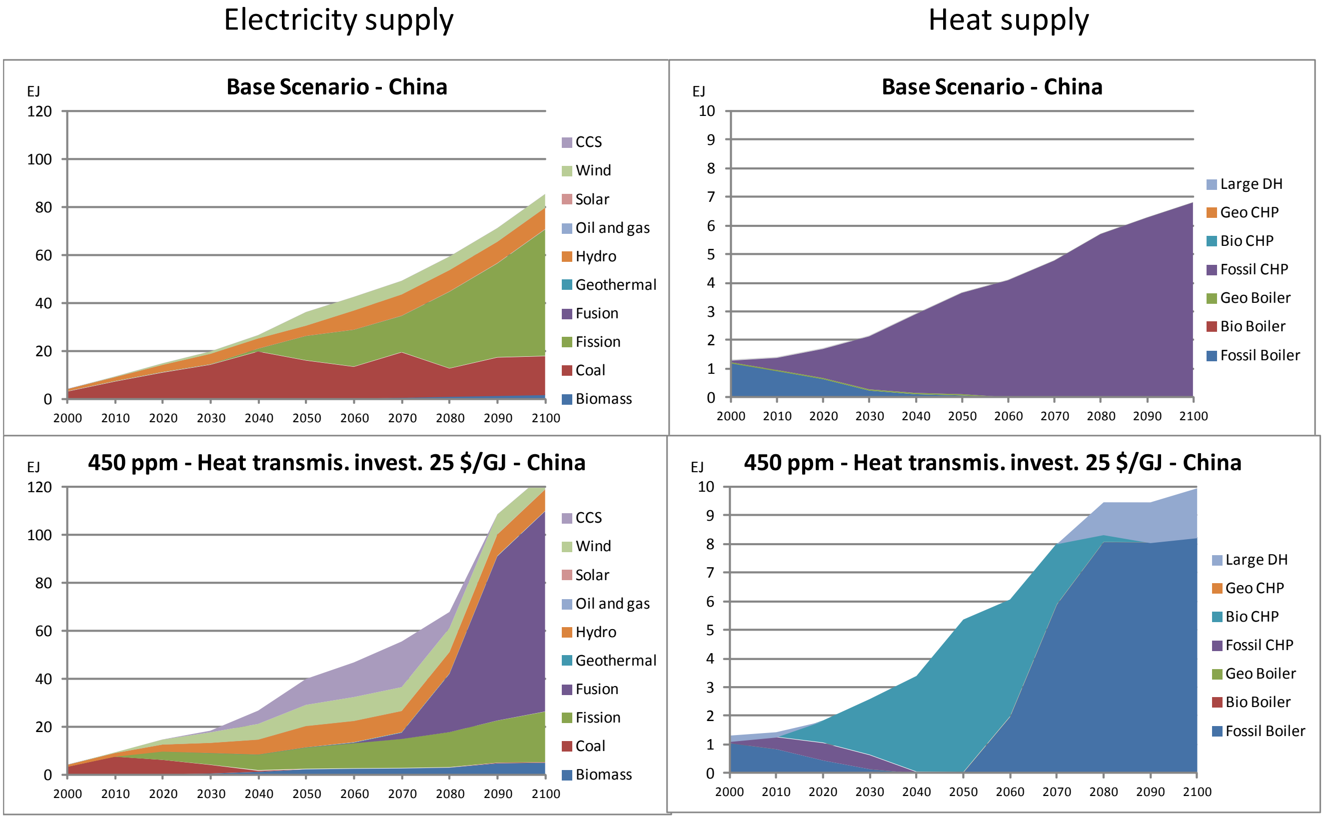


Figure 5.4. EFDA-TIMES results for electricity and heat supply in China 2000-2100. Base Scenario and scenarios with emission constraints.

Location of conventional fossil power near urban centres suitable for large district heating systems is still an important option, although the role of this technology is decreasing.

Many systematic studies using different TIMES models and similar models will be necessary to gain experience on the proper numerical values for infrastructure technology parameters on costs and performance.

- Technologies dependent on large-scale heat distribution:
- Large thermal power stations (fossil or nuclear).
- Fossil power stations with CCS.
- Urban waste incineration
- Deep geothermal energy

5.5 Fusion to replace CCS with heat recovery

Some studies on the use of CHP from nuclear fission for large-scale urban district heating were made in the 1970s. The high temperature reactor was designed for both electricity generation and process heat, but also the light water reactor could be used for combined production (IAEA, 1977).

The key parameter for the extraction of heat from extraction-condensing power stations is the power loss ratio, i.e. the loss of electricity load per unit of heat extracted. If the heat loss ratio is higher for a nuclear station than from available coal or gas fired stations, it is cheaper to extract heat from these stations. The heat loss ratio from fossil fuel fired stations has been very constant during the last decades, about 0.15. In the 1970s and 1980s there were wide range of assumptions of the heat loss ratio from nuclear extraction-condensing units, but all these studies may be outdated, taking into account the development of steam turbines for nuclear reactors during the last decades.

In the framework of the programme on Socio-Economic Research on Fusion (SERF), which was adopted by the EU, DG XII 1n 1997, one of the first studies concludes: “If fusion power is assumed available in a model of the Western European energy system, it emerges as an economically viable option in the case of CO_2 reduction policy. This analysis is based on various levels of global CO_2 stabilisation. Fusion power becomes competitive at cost of ECU 30 to 70/t CO_2 (Ecu95 values, Ecu90 25 to 60/t $CO_{2\ ...}$). Several variants with different discount rates, variants with a large potential of renewable energy and ample fossil fuel availability, etc. have been analysed.” (Lako et al., 1999).

Neither in this model study using MARKAL scenarios until 2100, nor in the range of long-term scenarios that were surveyed, the technology option of large-scale urban district heating was considered. In some of these long-term studies technology development was endogenised (Lako et.al.1998). The development of district heating grids, which would require a detailed treatment of urban geography, has apparently never been endogenised in long-term energy models.

The access for CHP from future fusion power to large-scale urban district heating grids, which could be developed during the next half-century, would improve the relative position of fusion power compared to the competing technologies, but it would not drastically change the conclusions of the study.

An early study (Hazelrigg and Coleman, 1983) titled “A Preliminary Examination of the Economics of Cogeneration with Fusion Plants” – with time horizon 2030, assuming that fusion reactors would be available from 2010 – concludes that fusion can “provide increased economic incentive to the implementation of cogeneration systems. Conversely, cogeneration improves the economics of fusion”. This article appears to use the prospect future fusion power as a driver for the development of CHP for district heating in the Mineapolis/St.Paul metropolitan region in the US.

Today, CCS may be used as a driver for the development and expansion of large-scale district heating systems, which are currently widespread in Northern and Eastern Europe, Korea and China, and with large additional potentials in North America. If fusion will replace CCS in the second half of the century, the same infrastructure for heat distribution can be used, which will support the penetration of both technologies.

In addition, district heating systems with CHP and heat storages offer some of the flexibility in electricity generation that is required for wind power and other intermittent electricity generation.

In contrast to nuclear fission with light water reactors, which operate at relatively low temperatures, the steam parameters for fusion – with temperatures in the range 600-800ºC – are similar to advanced coal or combined cycle gas turbines. Fusion units will operate as very large base-load units, and the unit size will be 1.5 GW, similar to LWR units or 2-3 large coal units. This is suitable for large-scale combined heat and power (CHP) for urban district heating systems, which need several decades for development, mainly by interconnection of existing smaller systems. In addition, fusion reactors will be suitable for other types of co-generation, e.g. catalytic hydrogen generation.

Both CCS and fusion may benefit from infrastructure already developed for other purposes. In the next decades CCS can be a driver for the development and expansion of large-scale district heating systems, which are currently used for distribution of heat from fossil-fuel combined heat and power and urban waste incineration. If fusion will replace CCS in the second half of the century, the same infrastructure for heat distribution can be used, which will support the penetration of both technologies.

5.6 New EFDA-TIMES version, May 2011

While the unconstrained results for EFDA-TIMES December 2009-version showed dominance of nuclear fission, the results for the new version, May 2011 is very different. Figure 5.5 compares the two versions for Europe. In the new version, there is very little fusion electricity by the end of the century. Also CCS has disappeared in the new version. In this version solar and wind become the dominant technologies instead of nuclear fission. However, in both versions infrastructure may be a weak point.

Figure 5.6 shows the same results for all regions in the world. The changes are similar. In some regions there will still be a significant fusion capacity by the end of the century. Figure 5.7 shows similar results for China, which is fastest growing region with a temperate climate.

Table 5.2 shows the data for central solar thermal technologies in EFDA-TIMES December 2009 and the new technology that was introduced in version May 2011. The new technology has slightly lower investment cost that is valid from 2020 instead of 2025. On the other hand, the fixed operating cost is slightly higher.

Table 5.2. Technology data for central solar thermal.

	ESOLTHC105	ESOLTHC110
Investment cost, $/kW	3600	4700
2010		3650
2020		2225
2030	2300	
2050	2300	
Fixed operating cost $/kW	36	67
2010	23	62
2020	23	29
2030	23	
2050	23	
Variable operating cost	0	0
Lifetime	30	30

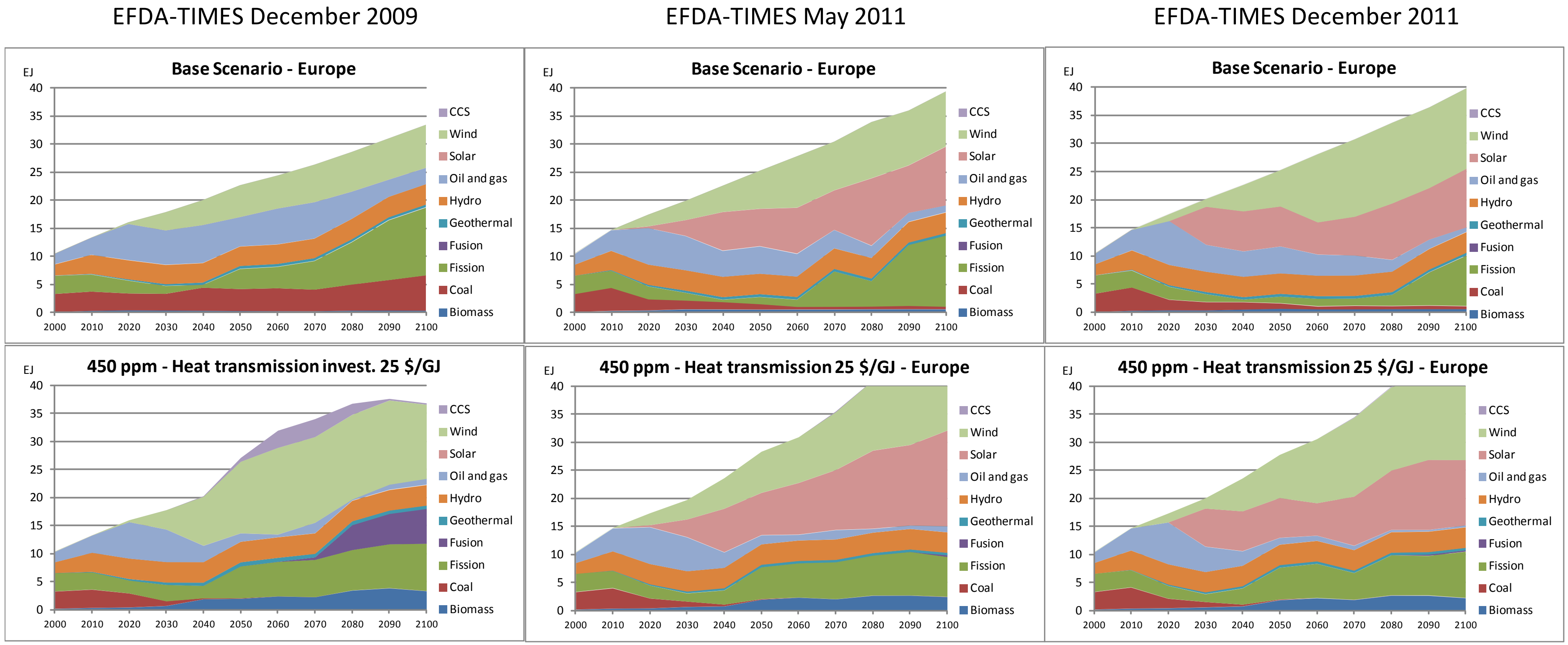


Figure 5.5, EFDA-TIMES results for Europe. Comparing versions.

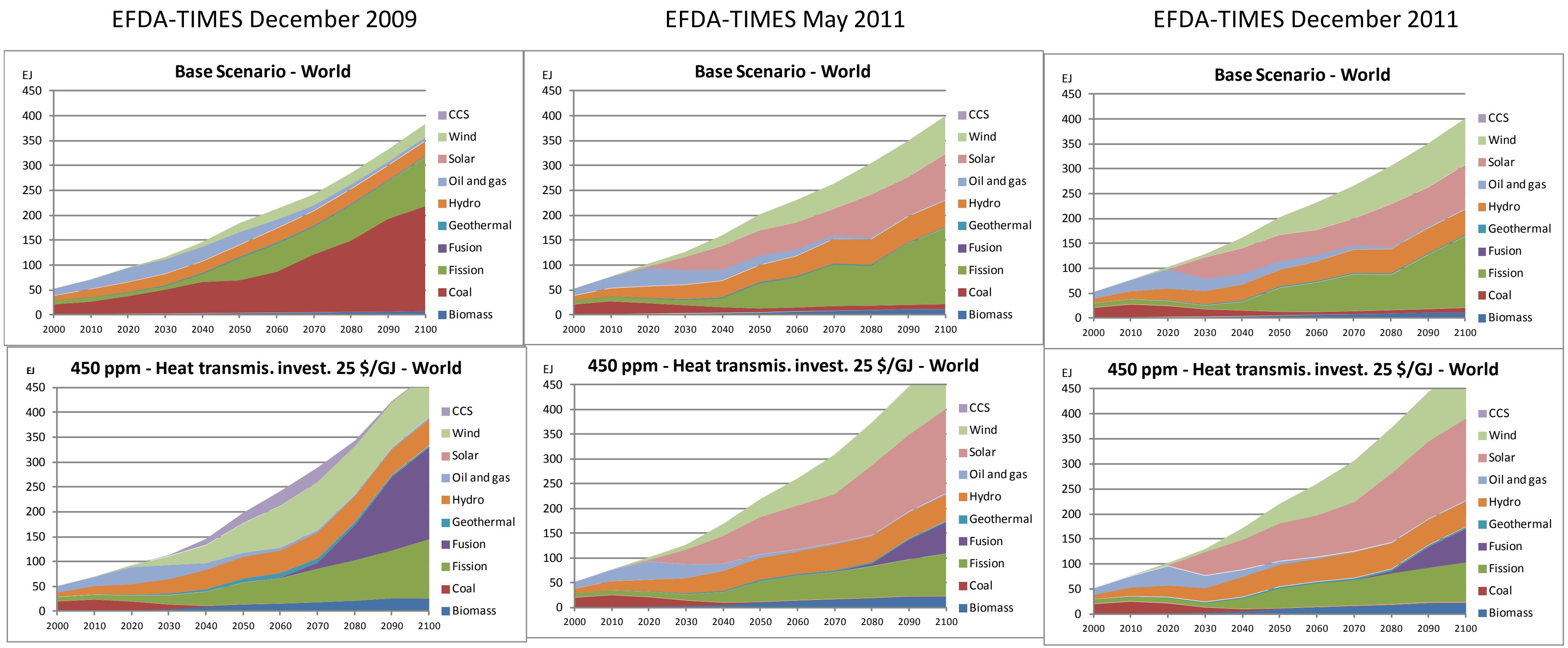


Figure 5.6. EFDA-TIMES results for all regions. Comparing versions.

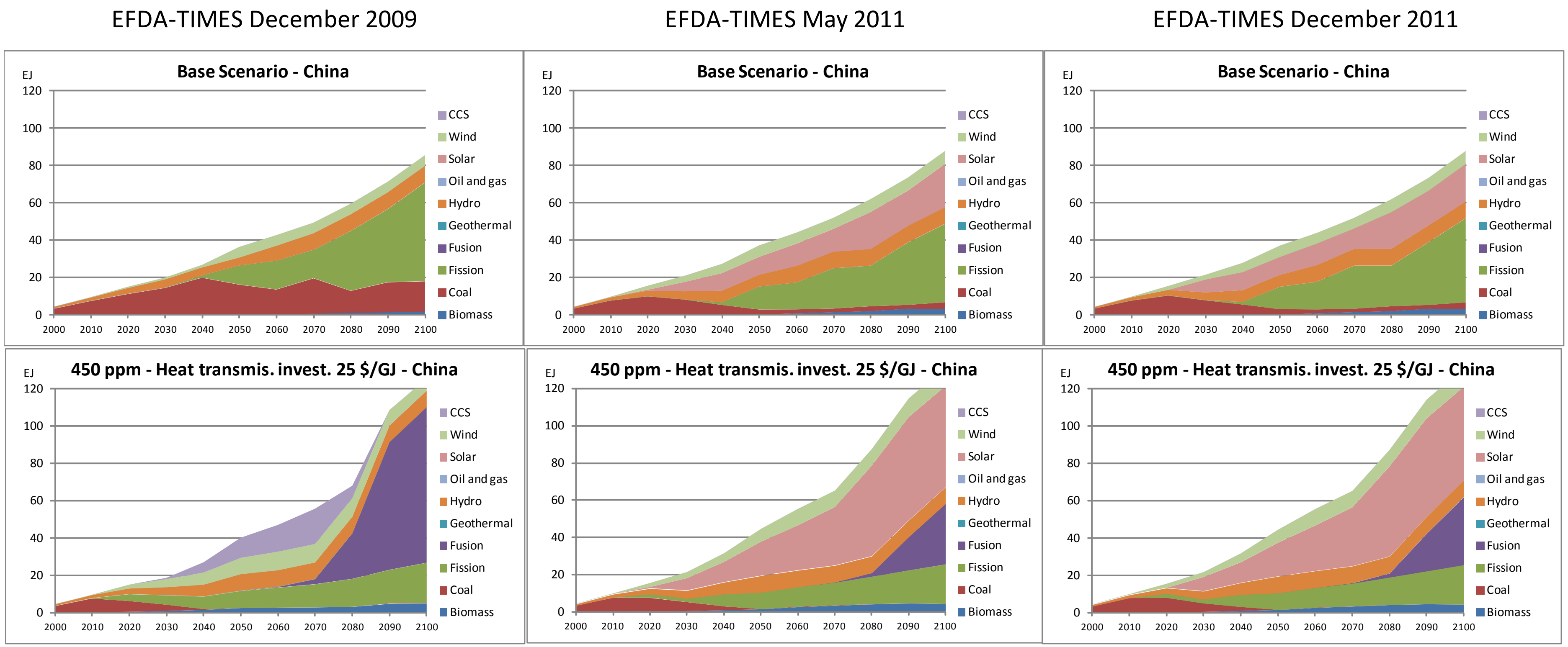


Figure 5.7, EFDA-TIMES results for China. Comparing versions.

5.7 Competition between fusion and fission in CO_2 constrained cases

Table 5.3 shows the objective value of the different scenarios in trillions of US \$. The objective value of Base scenario with fewest constraints is 0.99 % lower than the background scenario. The most constrained scenario – maximum 5% nuclear fission in all regions from 2030 is 0.21 % higher than the background scenario. The results for Biomass_high are unexpected. The larger biomass potentials is a relaxation of the constraints, which should lead to a lower objective value. So far, these values have not been further checked.

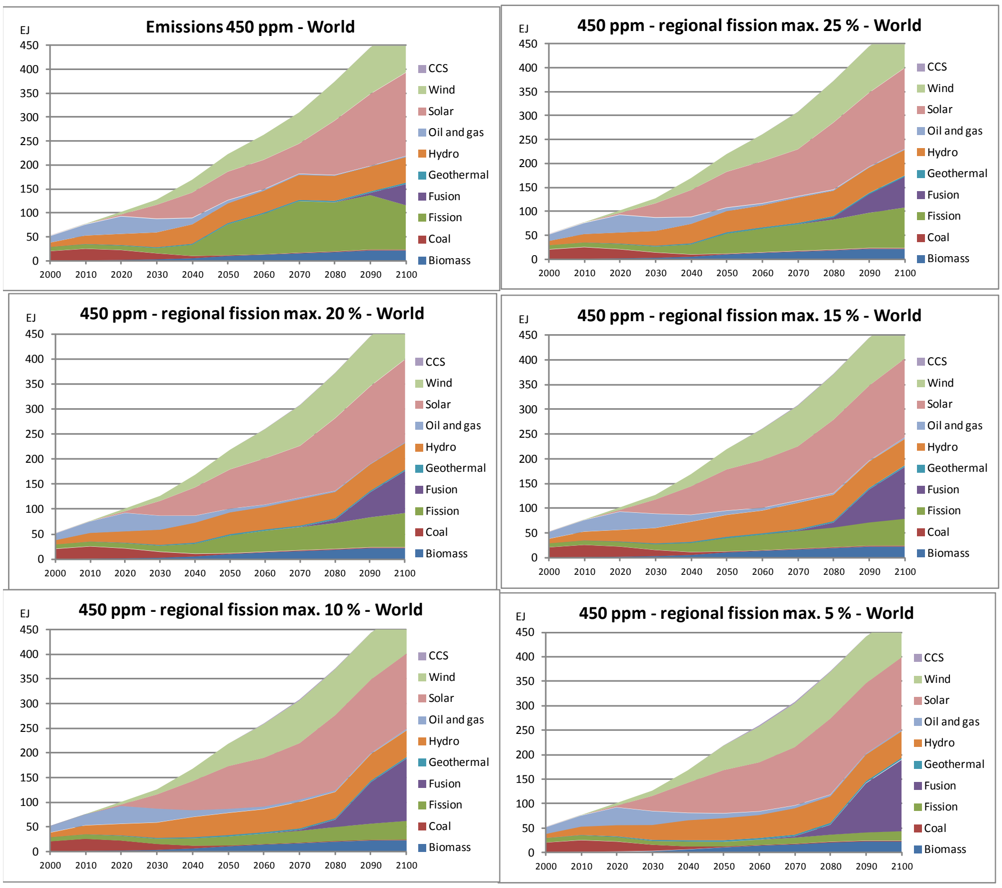


Figure 5.8. EFDA-TIMES results for all regions. Sensitivity to regional nuclear fission constraints.

The mix of electricity generation for this sensitivity analysis is shown in Figure 5.8. As nuclear fission becomes increasingly constrained – ranging from maximum 30% to 5% of the generation mix, more room is left for fusion by the end of the century. However all types of regional thermal generation are reduced considerably by the massive penetration of large-scale wind and solar power, mainly from more remote regions.

Table 5.3. EFDA-TIMES:Objective value

Selected Scenarios	Objective value Base	Emi550	Emi450	Background scenario=100 Base	Emi550	Emi450
Base	180.15	180.38	181.82	99.01	99.14	99.93
NucReg30		180.44	181.91		99.17	99.98
NucReg25		180.47	181.94		99.19	100.00
NucReg20		180.50	182.00		99.21	100.03
NucReg15		180.55	182.07		99.24	100.07
NucReg10		180.62	182.17		99.27	100.12
NucReg05		180.73	182.33		99.33	100.21
NucReg25 - Heat 50$/GJ		180.46	181.94		99.19	100.00
NucReg25 - Heat 25$/GJ		180.44	181.91		99.17	99.98
Biomass_High		181.67	183.05		99.85	100.61

5.8 Regional objective values – comparing global TIMES results

Figure 5.9 shows the latest amendment to the Excel workbook for global models in TIMES (i.e. EFDA-TIMES and TIAM) as mentioned in Section 1.1. This workbook is used to manage the dd-filed that are created by VEDA-FE with documentation of assumptions and results. A small part or the results is stored in a database sheet in the workbook. These results are regional objective values divided into investment, fixed and variable costs, etc. The results in the graph in Figure 5.9 are comparing two cases, which are looked up from the database. The database and graph are flexible concerning the regional breakdown of the global models. The current version covers EFDA-TIMES/ETSAP-TIAM (15 regions), TIAM-World (16 regions) and the new version of EFDA-TIMES (17 regions) from February 2012.

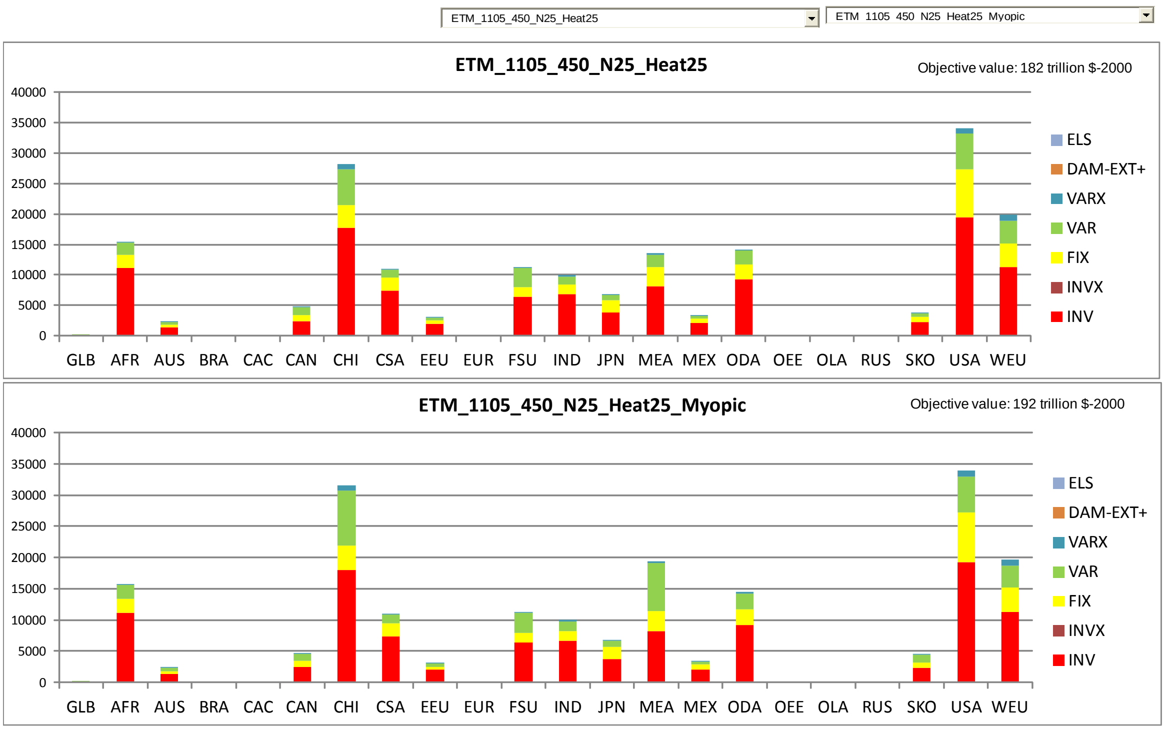


Figure 5.9. Regional objective values – comparing global TIMES results .

The GAMS code for TIMES reads the dd-files and writes all sets, parameters, equations and variables (results) into a the standard GAMS result file in gdx format. A small program, gdx2veda, which comes with the GAMS software using a definition file, e.g. times2veda.vdd creates the

<case>.vd files

to be imported into VEDA_BE. This file is very large and can hardly be read outside VEDA_BE. Table 5.4 shows a small version of the dd-file to display only regional objective values. With less than 256 items the regional objective values can be stored in an Excel database (Version 2003).

Table 5.4. gdx2veda definition file for regional objective values.

```
* TIMES objective value GDX2VEDA Set Directives

[DataBaseName]
 TIMES

[Dimensions]
 Attribute        attr
 Commodity        c
 Process          p
 Period           t
 Region           r
 Vintage          v
 TimeSlice        s
 UserConstraint  uc_n

[ParentDimension]
 Region Commodity Process

[Options]
SetsAllowed Commodity Process
*Scenario SCENCASE
*ValueDim 2
not-0 var_fin var_fout var_act var_actm cost_flo cost_act

[DataEntries]
* VEDA Attr     GAMS              - indexes -
*** Costs
  ObjZ          ObjZ.l
  Reg_wobj      reg_wobj          r c uc_n
```

5.9 Variants of the objective function

The recent versions of TIMES (from Version 2.8.0 – August 2008) have introduced Time-Stepped TIMES with limited foresight, in contrast to full foresight over the time horizon. This feature is controlled by two statements in the TIMES run file, TIMESTEP 20 meaning that each step will be 20 years and OVERLAP 10, meaning that each step will overlap the next with 10 years. Instead of a single optimisation covering the 100-years horizon, there will be 10 optimisations. However, this will be much faster, because the running time increase more than proportionate with the size of the problem.

The constrained case with CO_2 constraints to 450 and maximum 25 % nuclear fission in each region has been used to demonstrate the myopic version of the optimisation.

The objective value is increased by about 5 %, from 182 trillion \$ to 192 trillion \$, which indicates a less efficient optimisation. It has only a minor impact on the generation mix. In Figure 5.10 for Europe Nuclear fission will recover earlier by the mid-century.

Table 5.5. Run file for timestepped TIMES.

Run file
Initialisation
`$ SET TIMESTEP 20`
Set time slices, include dd files, etc.
`$SET RUN_NAME '`<Version name>`'`
`G_OVERLAP = 10;`
`g_dyear = 2000;`
Finalisation

Electricity supply

Heat supply

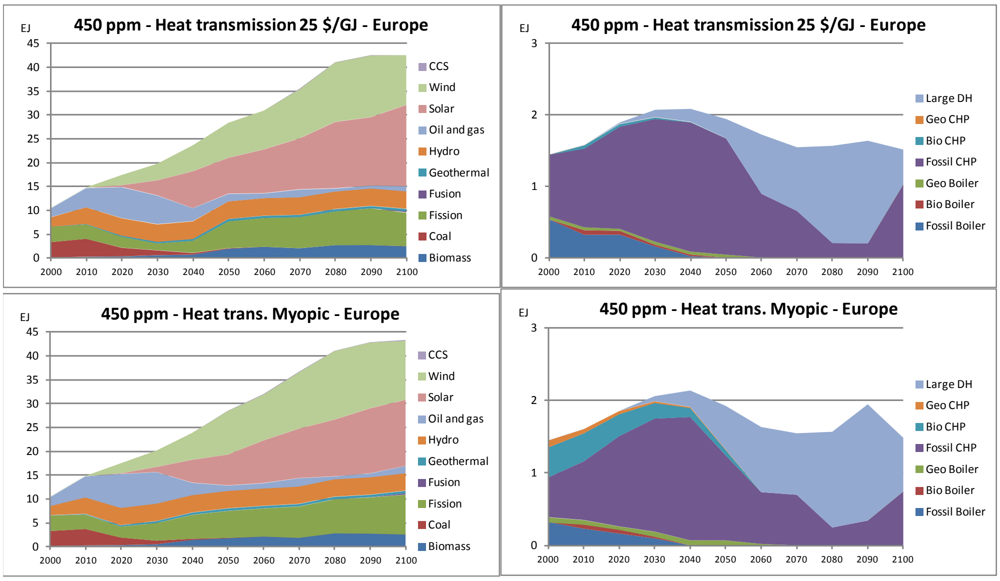


Figure 5.10. Comparing results for full foresight and myopic optimisation.

6 Topology and data for selected technologies in EFDA-TIMES and ETSAP-TIAM

Concerning the electricity industry, fusion fits well into the traditional model, where large-scale generating units are located near large population centres, e.g. coal or nuclear fission within few hundred kilometres from large urban centres. It is neither dependent on a high-capacity continental-wide transmission network (necessary for large-scale wind or solar), nor local ‘smart grids’ solutions required for distributed generation. Other technologies are a larger challenge to the model development.

6.1 Long-distance electricity transmission

The massive penetration of large-scale solar and wind technologies in the latest version of EFDA.TIMES – in contrast to the previous – indicates that this issue need to be much further addressed. The preliminary conclusion is that fossil fuels with CCS, wind power, large-scale solar, nuclear4 fission and fusion are similar in costs. This means that the balance between them cannot be found by the optimisation focusing primarily on conversion technologies.

In the current model it is implicitly assumed that transmission costs and losses are included in the parameters for these technologies. Within this model framework it is possible to find a balance between the technologies in a systematic sensitivity analysis with variation of the cost parameters for large-scale solar and wind – including the transmission to the population centres.

6.1.1 Electricity transmission in EFDA-TIMES and TIAM

So far, EFDA-TIMES and TIAM did not consider technologies for electricity transmission and distribution. In general, electricity is generated near the demand and the interpretation of electricity generating technologies is that they include transmission and distribution. The only attempt to consider electricity transport is the existence of two commodities for electricity, ELCC (central) and ELCD (decentral).

The introduction of long-distance transmission will require a third commodity, ELCT (electricity for long-distance transmission). Transmission processes then have ELCT as input and ELCC as output with parameters for efficiency, e.g. 0.95 and cost parameters. This commodity shall replace ELCC in interregional trade and as output from the major resource-based technologies, in particular off-shore wind and large-scale solar.

6.1.2 Extensions and updates of the Pan-European TIMES (PET) model

The Pan European TIMES (PET) model was originally developed as a part of the EU-NEEDS (New Energy Externalities Developments for Sustainability), Research Stream 2a: “Energy systems modelling and internalisation strategies, including scenarios building” 2004-2008. It covers some 30 European countries that are modelled with the same structure. It has been further developed in a series of EC funded projects (RES2020, REACCESS, PLANETS, REALISEGRID).

In particular the two projects REACCESS (Risk of Energy Availability: Common Corridors for Europe Supply Security) and REALISEGRID are focusing on the development of a trans-national transmission grid infrastructure, which will allow electricity transmission remotely located solar and wind resources to population centres. The lasted project REALISEGRID was finished early in 2012 (Final conference

February 2012),, and the published results may be utilised for aggregated technologies and parameters for global models such as EFDA-TIMES.

6.2 EFDA-TIMES with large-scale CHP

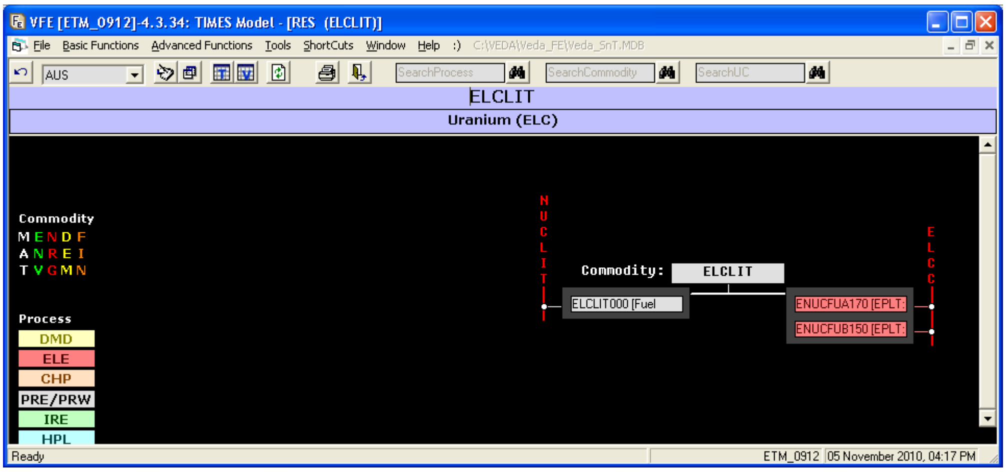


Figure 6.1. VEDA: Fusion processes and fuel (lithium).

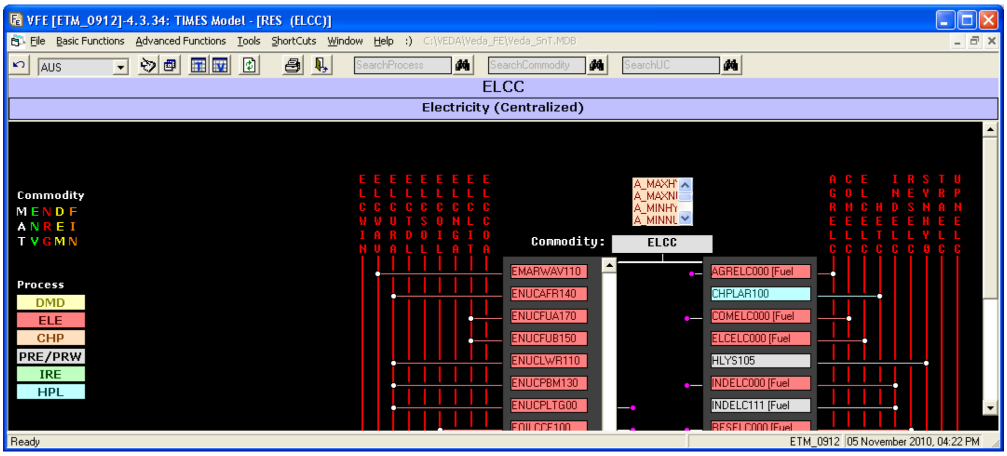


Figure 6.2. Central electricity processes - with central CHP

Aggregate technologies for large-scale CHP and heat transmission/distribution

- New Processes
- Large CHP/"virtual heat pump"
- Heat transmission
- New commodity
- HETC

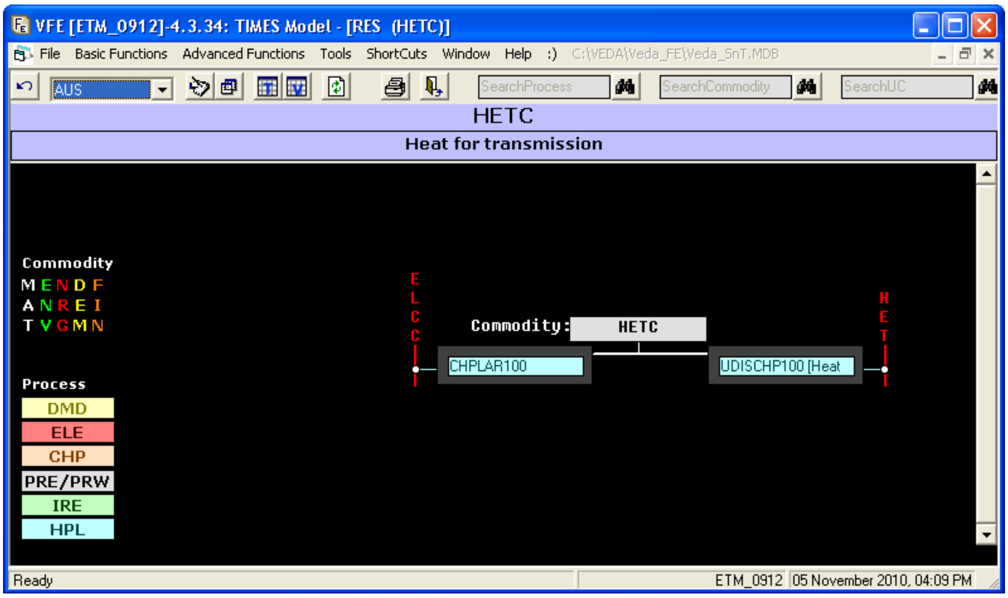


Figure 6.3. Flow of central heat.

Aggregate technologies for large-scale CHP and heat transmission/distribution

– HETC (new) Heat supply from large CHP to urban grids.

– Regional constraints depending on climate and heat market in Base scenario.

– HET (current) All heat – from rooftop solar panels to institutional distribution network and small district heating grids

– Next step: Adding intermediate heat network(s),

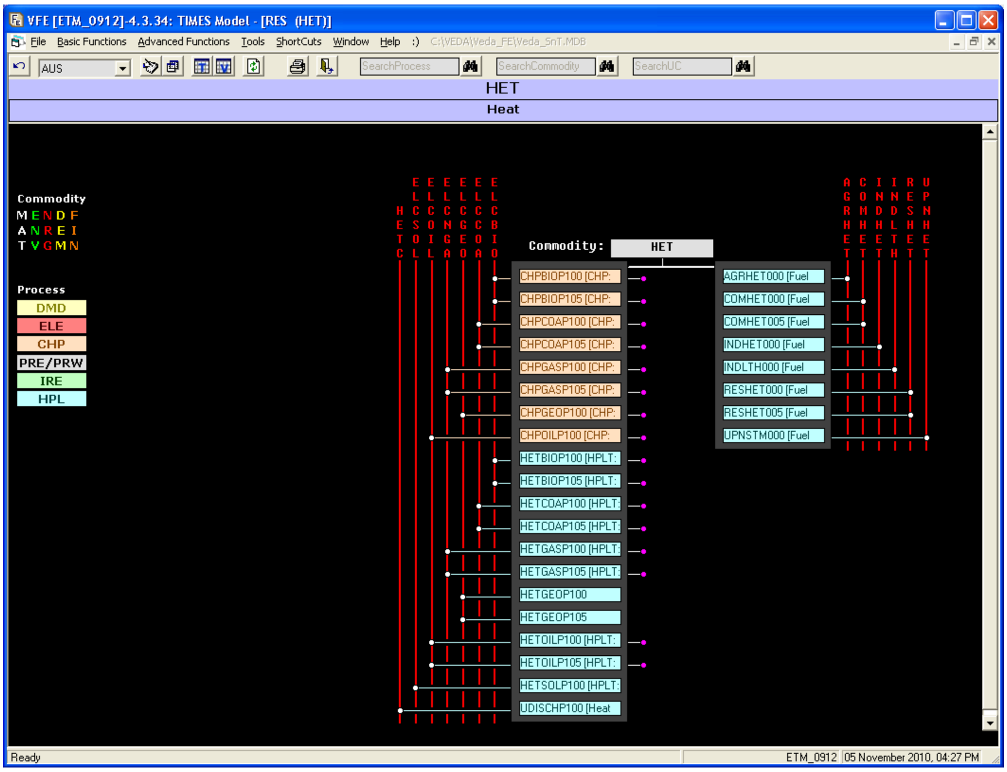


Figure 6.4. Aggregate technologies for large-scale CHP and heat transmission/distribution.

6.3 Residential heating in EFDA-TIMES and ETSAP-TIAM

Investment cost for house installations are given as $/GJ annual flow. Examples from TIAM:

- Oil/gas burner, standard (eff: 0.78) 55 $
- Oil improved eff 0.95, 72 $
- Gas improved, eff. 0.95, 98 $
- Resistance electrical heating 55 $
- Heat pumps eff. 4.1, 157 $

The analysis of this part of the model is still very preliminary, which indicates that the heating sector may not have been the focal point of previous analyses using global TIMES models.

Table 6.1. Key parameters for residential heating technologies.

Technology	Efficiency	Invest. Cost, $/GJt	Efficiency	Inves. Cost, $/GJt
Biomass boiler				
Oil boiler				
Gas boiler				
Electric resistance heating	0.95	0.7		
Heat pump				
District heat				

Table 6.2. Technology chain for residential heat.

	Total	Primary Energy/Transmission	System/Distribution	Final Energy	Household systems
Efficiencies					
Biomass	0.61	1	1	1.00	0.61
Oil	0.91	1	1	1.00	0.91
Gas	0.86	1	1	1.00	0.86
Electricity	0.83	0.94	0.93	1.00	0.95
Heat pump	2.89	0.94	0.93	1.00	3.30
DH, small	0.86	1	0.90	1.00	0.96
DH, large	4.56	5.00	0.95		
Costs, €/GJ					
Biomass	26.39			10.00	10.00
Oil	15.49			10.00	5.00
Gas	15.81	8.00		2.00	5.00
Electricity	22.86	13.89	5.56		2.00
Heat pump	23.79	13.89	5.56		10.00
DH, small	18.76	8.00	5.00		5.00
DH, large	13.25	13.89	5.00		

This part of the model needs much further development with focus on the consistency of parameters for competitive as well as complementary technologies.

6.4 Decentral electricity in EFDA-TIMES and ETSAP-TIAM

Table 6.3. Technology chain for distributed electricity.

	Total	Primary Energy/Transmission	System/Distribution	Final Energy	Household systems
Efficiencies					
PV	0.61	1	1	1.00	0.61
Local wind	0.91	1	1	1.00	0.91
Local biomass	0.86	1	1	1.00	0.86
Fuel cell H2	0.83	0.94	0.93	1.00	0.95
Fuel cell CH4	2.89	0.94	0.93	1.00	3.30
Gas turbine	0.86	1	0.90	1.00	0.96
Elec. market	4.56	5.00	0.95		
Costs, €/GJ					
PV	26.39			10.00	10.00
Local wind	15.49			10.00	5.00
Local biomass	15.81	8.00		2.00	5.00
Fuel cell H2	22.86	13.89	5.56		2.00
Fuel cell CH4	23.79	13.89	5.56		10.00
Gas turbine	18.76	8.00	5.00		5.00
Elec. market	13.25	13.89	5.00		

Decentral and distributed electricity are technologies, which have received very much interest in recent years. So far, there representation in global models optimisation has been quite weak, although several models includes a large number of technologies for small-scale cogeneration.

7 TIMES model input

This paper is a summary of documentation of parameter input to different versions of ETSAP-TIAM and EFDA-TIMES between 2005 and 2011.

TIMES version 2.40 (October 2007) introduced the switch for input only to be used in the TIMES run file before the $BATINCLUDE statements for data input, see Table 7.1, which will create a gdx file only containing sets and parameters from the following .dd files.

The switch is described in c:\VEDA\Veda_FE\Gams_srcTIMESv312\Version.log:
"- Added switch for data preparation only (for ANSWER imports): INTEXT_ONLY"

The use of the feature is described by VEDA Support:

http://www.kanors.com/VedaSupport/index.htm

VEDA-FE > ADVANCED TECHNIQUES > COMPARING INPUT DATA

The feature also enables a comprehensive documentation of all input as well as comparison of different versions of TIMES models.

7.1 Creating gdx and database files

Table 7.1. Files used to run TIMES input.

Run file

Initialisation

```
SET ALL_TS/ANNUAL seasons seasons-diurnal /
* Generate gdx files for input only
$SET INTEXT_ONLY YES
$SET PREP_ANS YES]
$BATINCLUDE base.dd
$BATINCLUDE <SUBRes, SysSettings, Demand, Base Case scenario>.dd
SET MILESTONYR /2000,2005/;
$SET RUN_NAME '<Version name>'
```

TIMES_input.cmd

```
Call GAMS <Case name>.RUN IDIR=<TIMES folder>\ GDX=GamsSave\<Case name>
```

The gdx files can be read by the tools that is shipped with GAMS and converted to Excel or Access databases, using gdxviewer.exe, gdx2xls.exe or gdx2access.exe.

The Excel workbook created by gdx2xls contains a sheet 'Table of Contents' that list all set and parameter names with Type (set/parameter), Dimension, Count (number of items and an Explanatory text. The names links to sheets containing lists of items.

This structure contains all the information that is used by TIMES for the optimisation. Details of different model cases can be read by Excel formulas (e.g. VLOOKUP functions) and used in a new spreadsheet.

The following subsection refers to files and data used for the TIAM version, TIAM_Dubrovnik, which was used for a presentation at 5th Dubrovnic Conference on

Sustainable Development of Energy, Water, and Environment Systems in September 2009. It was later published in Applied Energy (Føyn et al 2010).

The file `base.dd` was created by VEDA-FE, version. The VEDA-FE default location is c:\VEDA\Veda_FE\Gams_WrkTIMES\. To use `base.dd` (and the other `.dd` files for a base run or reference scenario) they should be removed to a subfolder <VEDA template folder>\dd. Similar to the default location there should be a subfolder `dd\GamsSave` for location of .gdx files created by TIMES and GAMS. The Excel file created by gdx2xls is located in the same folder.

7.2 Contents of input database files

The first sheet "Table of Contents" lists all set and parameter names with Type (set/parameter), Dimension, Count (number of items and an Explanatory text. The names links to sheets containing lists of items.

Dimension 0 contains scalar parameters only. These names all links to the second sheet "Scalar", which contains 33 items. Most of these are formal. Figure 7.1 shows some more significant values, e.g. STARTOFF year and "Year to discount to".

	A	B	C
2	Parameter	Value	Explanatory text
14	G_DYEAR	2000	Year to discount to
15	G_ILEDNO	10	1/threshold at which to ignore ILED
16	G_NOINTERP	0	Turn off interplation
17	G_OVERLAP	0	Overlap of stepped solutions (in years)
18	G_TLIFE	10	Default technology life if not provided
19	G_VINT	0.1	% annual change in input data for vintaging
31	STARTOFF	2005	

Table of Contents | Scalar | ACT_BN

Figure 7.1. TIMES model input. Scalar sheet

Dimension 1 lists 115 sets and 36 parameter names. Some of these sets are formal listings (e.g. the 239 years from 1964 to 2200). Others are basic listings of the key sets of the model version. The latter type of sets is shown in Figure 7.2.

Few parameters of dimension 1 are interesting for the model user. Figure 7.3 contains the parameters for beginnings, middle, end and length of each period, plus some technical constants for the climate module.

Dimension 2 lists 50 sets and 20 parameters. The sets COM_DESC and PRC_DESC list commodities and processes in each region with region-based descriptions. The parameter CM_DEFAULTS contains 36 year-specific values (the element names are different from CM_CONST). The parameter PRC_CAPACT contains 10122 items, which take only two values, either 1 or 31.526 (8760*3600/1000000).

Dimension 3 lists 69 sets and 66 parameters. The non-empty set combines the elements from the basic sets (regions, process, commodities, etc.) with up to 52008 elements ('Commodities in/out of a process). These are elements in the topology used by GAMS. The parameter COM_PROJ contains the regional demand for some 50 commodities.

(The commodities UNH is set to the value 0.0001 for all 5-year steps until 2050, and UPH to the same value for the regions AFR, CSA, MEA, and ODA).

G_DRATE (Discount rate for a currency) is set to 0.05.

NCAP_LIFE (Technical lifetime of a process) is set to values between 5 and 100 years for some 600 processes in each region, and 'PRC_RESID (residual capacity) is set to values above EPS for 60 processes and years between 2005 and 2100 for region WEU. The total number of elements for all regions and years is 13451.

	Name	Type	Dim	Count	Explanatory text
11	ALL_REG	set	1	18	External + Internal Regions
12	ALL_TS	set	1	10	The universe for time-slices
62	CM_HISTS	set	1	17	Historical CO2 concentration and incremental forcing quantities
83	COM	set	1	515	Commodities
105	COM_GRP	set	1	735	Commodities & Groups
122	COM_TYPE	set	1	5	List of main commodity types groups
127	COSTAGG	set	1	24	Types of cost aggregations
154	ENV_GRP	set	1	2	List of emission groups
238	MAT_TYPE	set	1	5	List of material types
313	NRG_FORM	set	1	3	List of energy forms
315	NRG_GRID	set	1	4	List of grid types
367	PRC	set	1	1654	Processes
378	PRC_GRP	set	1	18	List of process groups
412	REG	set	1	16	Region
577	UNITS	set	1	19	Units

Figure 7.2. Sets Dimension 1

	Name	Type	Dim	Count	Explanatory text
16	B	paramete	1	36	Beginning year of each model period
55	CM_CONST	paramete	1	13	Climate module constants
135	D	paramete	1	36	Length of each period
148	E	paramete	1	36	Ending year of each model period
232	M	paramete	1	36	Middle year of each Period

Figure 7.3. Parameters Dimension 1

	A	B	C	D
1	TOC			
2	TOP	(set)	Topology for all process	
3	REG	PRC	COM	IO
41831	WEU	CHPGASP00	ELCC	OUT
41832	WEU	CHPGASP00	ELCCH4N	OUT
41833	WEU	CHPGASP00	ELCCO2N	OUT
41834	WEU	CHPGASP00	ELCN2ON	OUT
41835	WEU	CHPGASP00	ELCNGA	IN
41836	WEU	CHPGASP00	HET	OUT

Figure 7.4. Topology data for natural gas CHP.

Dimension 4 lists 31 sets and 59 parameters. The sets are mainly combinations of sets with lower dimension. Most important is the set TOP ('Topology for all process), which contains the full topology description for all regions (44500 elements)

Dimension 5-8 lists 18 sets and 95 parameters. The only non-empty set is TOP_IRE ('Trade within area of study) with 6861 elements. Processes describing trade between two regions are added to the 4 dimension Region / Commodity / Other region / Same commodity, e.g. TU_ELCC_WEU_AFR_01 for electricity transmission from Europe to Africa.

The parameters ACT_EFF shows efficiencies for processes in each region. About half of the values have the value 1, the other half are real efficiencies with values different from 1.

The parameters ACT_BND and ACT_CUM contains data for bounds on annual or cumulated output from some 50-100 processes in each region. These are mostly 'mining' processes with resource constraints.

The parameter COM_ELAST (Elasticity of demand) shows values for some 20 commodities with potentially elastic demand. These elasticities are between -0.05 and -0.2. The 3-dimentional parameter COM_STEP (Step size for elastic demand) is set to the value 10 for both UP and LO.

The parameter FLO_DEL (Delivery cost for using a commodity) contains the value 1 for the process TRAELC000 and commodity ELCC for all regions.

The parameter FLO_EMIS shows process-specific emission factors for CO2, CH4, N2O and other emission commodities.

FLO_MARK is used for the commodity IFCH only. This is an intermediate commodity from processes in the petrochemical industry used as input to 'Existing Chemicals Tech'

FLOW_SHAR (Relationship between members of the same flow group) contains some 500 items for each region. Most of these are results of the base-year calibration. About 150 of these items are constraints for future years.

IRE_PRIC (Price of import/export) contains some 100 items for each region. Many values are not real data, e.g. 0.1 or 0.0001.

NCAP_AF ('Availability of capacity) contains some 500 items for each region. Most of these are set to 1, less that 5% af the values are different from 1.

VDA_FLOP (no description) contains some 400 items for each region. Some 30 % of these items are different from 1.

7.3 Comparison of model input

Another tool, gdxdiff.exe allows comparison of different but similar versions of TIMES.

The recommended command is:

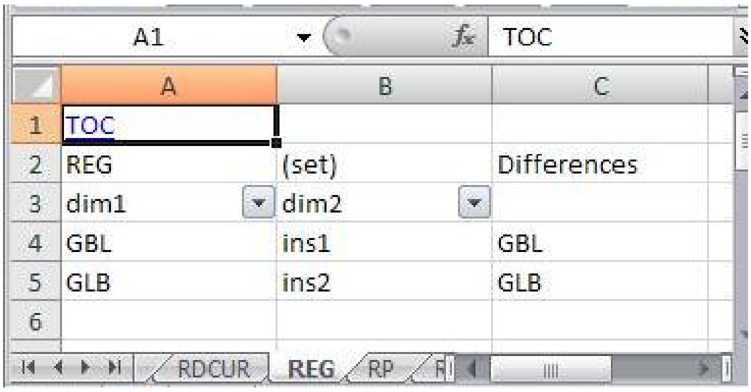
gdxdiff <compare version>.gdx <reference version>.gdx <compare version>_diff.gdx

To use the feature for a systematic analysis of the model development and detection of errors the selection of *compare* and *reference* versions as well as the naming conventions for files and folders are important.

Table 7.2. Manual and automatic comparison of TIMES model versions.

Compare version	**Reference version**
Model updates: Automatic generation of difference databases	
ETM_May11sept1_input.gdx	ETM_0912_Base_input.gdx
ETM_1103_Base_input.gdx	ETM_0912_Base_input.gdx
ETM_1011_Base_input.gdx	ETM_0912_Base_input.gdx
ETM_0912_input.gdx	EFDA-REL-2005-11-30_input.gdx
ETM_0809b_input.gdx	EFDA-REL-2005-11-30_input.gdx
ETM_0706_input.gdx	EFDA-REL-2005-11-30_input.gdx
ETM_2005_input.gdx (reconstruct)	EFDA-REL-2005-11-30_input.gdx.
Technology Chains: Manual comparison of versions in a spreadsheet..	
ETM_1105_Base_input.xlsx]- 06-09-11	BaseRun_input.xlsx -18-11-10
PET_0905_Ref_input.xlsx	PET-RES2020_input.xlsx

Table 7.2 shows a selection of updates of EFDA-TIMES to be compared with earlier reference versions, which has been used for a large number of scenario studies, reports and presentations.



A1 TOC

	A	B	C
1	TOC		
2	REG	(set)	Differences
3	dim1	dim2	
4	GBL	ins1	GBL
5	GLB	ins2	GLB
6			

RDCUR REG RP

Figure 7.5.Name of global region in Compare version (ins1) and Reference version(ins2)

The files <compare version>_diff.gdx may be converted to <compare version>_diff.xlsx using gdx2xls. Figure 7.5 shows an example of differences that disclose inconsistent naming of global region in ETSAP-TIAM from version TIAM_0812 (December 2008) and later.

The inconsistency that is shown in. Figure 7.5 has been further analysed. Checking all versions it was found for the naming of the global region:

GLB: TIAM_0712, TIAM_0807, EFDA-TIMES (all versions),

GBL: TIAM_0812, TIAM_0905, TIAM_0909, TIAM_Dubrovnik

7.4 Contents of Base-Year templates

The files ETM_BY_input.gdx or TIAM_BY_input.gdx are archived in subfolders to the VEDA template folder named C:\VEDA\VEDA_Models\<compare

version\dd\GamsSave, see Section 7.1 This archive structure is used to create the databases <reference version>_diff.gdx.

Table 7.3. Automatic comparison of Base Year data for ETSAP-TIMES and early TIAM versions with ETSAP-TIMES references.

	ETM_0511\...\ETM_BY_input	ETM_0912\...\ETM_BY_input
TIAM_0712\...\ TIAM_BY_input	c:\VEDA\VEDA_Models\TIAM_0712\DD\GamsSave\ETM_0511_BY_diff.gdx 4.3/13.5 MB 15-05-11. 126 sets and parameters with up to 80425 differences (NCAP_BND. 8280 TOP differences.)	c:\VEDA\VEDA_Models\TIAM_0712\DD\GamsSave\ETM_0706_BY_diff.gdx 3.3/9.9 MB 15-05-11. 131 sets and parameters with up to 27034 differences (COM_PROJ. 18218 TOP differences.)
ETM_1105\...\ ETM_BY_input	c:\VEDA\VEDA_Models\ETM_1105\DD\GamsSave\ ETM_0511_BY_diff.gdx/xlsx Missing.	c:\VEDA\VEDA_Models\ETM_1105\DD\GamsSave\ ETM_0912_input_diff.gdx/xlsx. Missing
ETM_1103_Base_input		c:\VEDA\VEDA_Models\ETM_1103\DD\GamsSave\ ETM_0912_input_diff.gdx/xlsx. Missing
ETM_1011_Base_input		c:\VEDA\VEDA_Models\ETM_1011\DD\GamsSave\ ETM_0912_input_diff.gdx/xlsx 0.4/0.9 MB 08-05-11 37 sets or parameters with up to 14980 differences (parameter UC_FLO)
ETM_0912_input	c:\VEDA\VEDA_Models\ETM_0912\DD\GamsSave\ ETM_0511_BY_diff.gdx/xlsx 3.9/12.4 MB 15-05-11 93 sets or parameters with up to 79485 differences (parameter NCAP_BND, 22687 TOP differences)	
ETM_0809b_input	c:\VEDA\VEDA_Models\ETM_0809\DD\GamsSave\ ETM_0511_BY_diff.gdx/xlsx 3.8/12.1 MB 15-05-11 91 sets or parameters with up to 79485 differences (parameter NCAP_BND, 22687 TOP differences)	
ETM_0706_input	c:\VEDA\VEDA_Models\ETM_0708\DD\GamsSave\ ETM_0511_BY_diff.gdx/xlsx 2.8/9.2 MB 15-05-11 85 sets or parameters with up to 80744 differences (parameter NCAP_BND, 13356 TOP differences)	

ETSAP-TIAM with reference to Table 7.3 compares the first available version of TIAM-ETSAP (TIAM_0712, December 2007).and selected updates of EFDA-TIMES with the first version from November 2005 and the December 2009-version, which has been used for publications and articles.

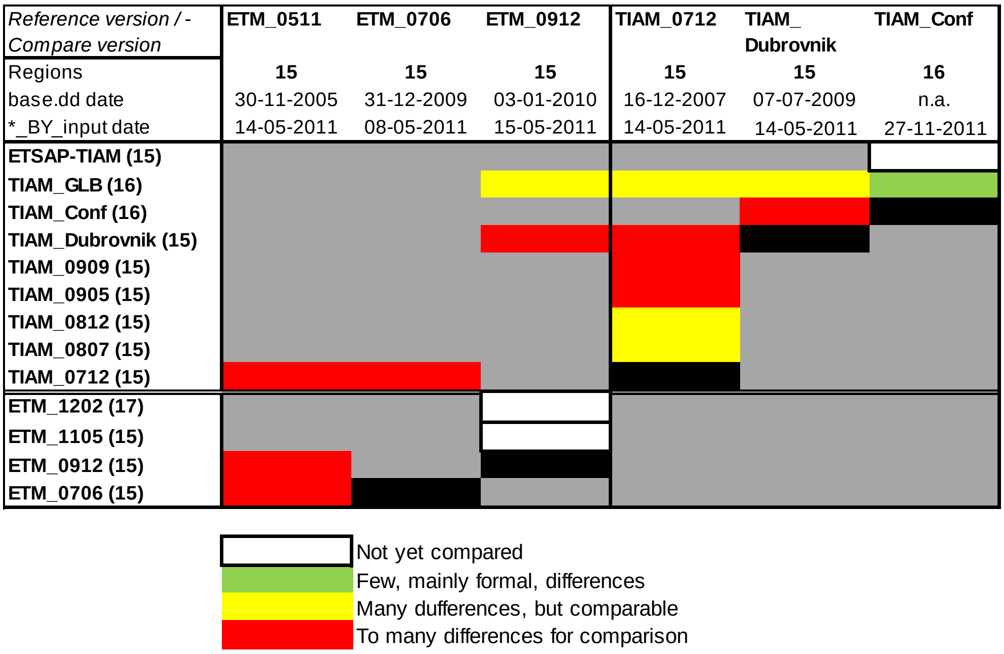


Figure 7.6. Comparing base year data for

7.5 Technology chains

The manual comparison of versions in a spreadsheet – as mentioned in Table 7.2 is used to document and analyse ‘technology chains’ e.g. from primary energy to heat or electricity supply or ‘well to wheel’ in transport. The aim is to document that data and energy flow structures for competing technology chains are consistent.

7.6 Recommendation

To archive the data necessary for documentation of input for each TIMES model only the base.dd and other .dd files for a base scenario need to be available for download. Using the TIMES run and command files the gdx and Excel databases can be created easily by users on computers with TIMES and GAMS installed. The size of a zip archive containing the TIAM_Dubrovnik base.dd file, run and cmd files is 0.9 MB. Including all .dd files for full Base Run the zip archive will be 2.7 MB.

8 Conclusion: Modelling fusion in the energy system

Contribution to Association Euratom - DTU, Technical University of Denmark, Department of Physics - Annual Progress Report 2011, SC-ER 41(12)/4.1, April 2012.

Within the Socio-Economic Research on Fusion (SERF) programme EFDA and the Associations are developing a multi-region global long-term energy modelling framework (EFDA-TIMES), which has been developed together similar models, which are used by the International Energy Agency (IEA), the US Department of Energy and several project under the European Union 6th and 7th Framework Programmes.

The technologies are organised into a network of energy flows linking demand and supply. Forecasts of energy demands in the various sectors come from global economic models. The energy system in these models is optimised by minimising total system costs subject to constraints reflecting infrastructure, technology availability and policy objectives, e.g. reduction of CO_2 and other greenhouse gasses. In these models the energy system is divided into the following main sectors: Upstream, Electricity, Industry, Residential, and Transport.

Figure 1 illustrates typical results from the EFDA-TIMES model. Electricity is generated by an optimal set of technologies, which are balanced by the selection of fuel prices, technology costs and constraints on resources and technology development. Fusion units will operate very similar to current large-scale thermal generating units for supply of industrialised regions and population centres, which now dominate electricity generation. New technologies will become significant earlier than fusion. Some of them are small-scale technologies located much closer to the consumers. Others are dependent on natural resources located in coastal regions with shallow water or deserts. The potential of these resources is huge by 2050, when fusion may become available, but their production varies with sun and wind, and they require very large investment in long-distance transmission to population centres. All these technologies will reduce the market share of large-scale thermal units, which includes fusion.

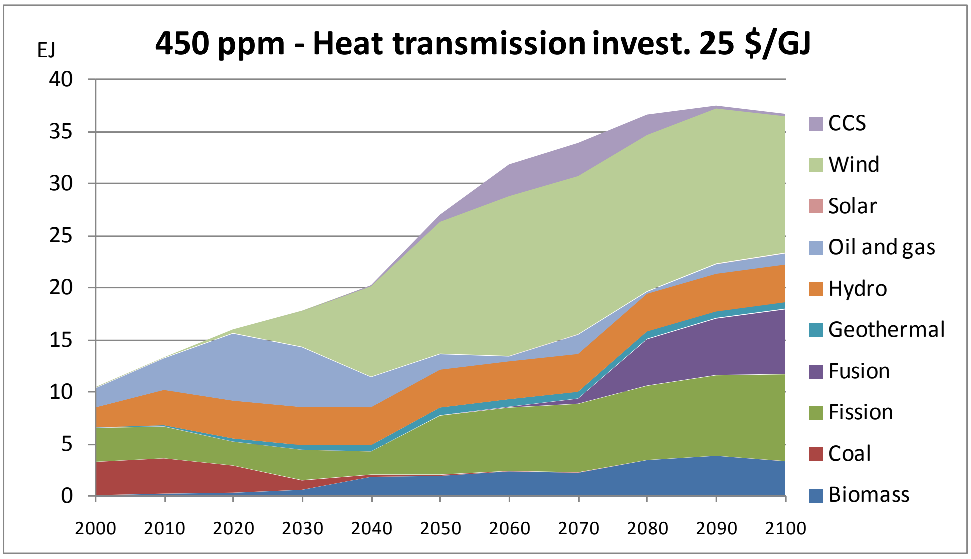


Figure 8.1. EFDA-TIMES model result for electricity generation in Europe 2000-2100.

The case shown in Figure 8.1is assuming that CO_2 emissions constrained at 450 ppm from 2050, maximum fission generation 25 % from 2030 and aggregated average investment in heat transmission for large-scale urban district heating at 25$ per GJ annual flow [Grohnheit et al. 2011].

The EFDA-TIMES model is a global model currently divided into 15 regions base year 2000 from IEA statistics and the time horizon year 2100. The ongoing development aims at revising the number of regions, update of starting year and enhancement of the description of technologies that are competing with fusion, in particular variable renewable and nuclear fission.

Contributions to EFDA-TIMES from the Systems Analysis Division (from 2012 part of the new institute DTU Management Engineering) are co-ordinated within the work on other TIMES-based models on the global and European level and contributions to the IEA Implementing Agreement ETSAP (Energy Technology Systems Analysis Programme) [Grohnheit 2011, Føyn et al. 2010]. These activities also include 2-3 PhD students.

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